The Giant Planets

- Jupiter, Saturn often the brightest “stars” in the sky
- Telescopes from Earth give good views.

<table>
<thead>
<tr>
<th>Distance (au)</th>
<th>Period (yrs)</th>
<th>Diameter (°)</th>
<th>Mass (Earth)</th>
<th>Rotation (hrs)</th>
<th>Tilt (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>24.0</td>
</tr>
<tr>
<td>Jupiter</td>
<td>5.2</td>
<td>11.9</td>
<td>11.2</td>
<td>318</td>
<td>9.9</td>
</tr>
<tr>
<td>Saturn</td>
<td>9.5</td>
<td>29.5</td>
<td>9.4</td>
<td>95</td>
<td>10.7</td>
</tr>
<tr>
<td>Uranus</td>
<td>19.2</td>
<td>84.1</td>
<td>4.0</td>
<td>14</td>
<td>17.2</td>
</tr>
<tr>
<td>Neptune</td>
<td>30.1</td>
<td>164.8</td>
<td>3.9</td>
<td>17</td>
<td>16.1</td>
</tr>
</tbody>
</table>

But (again) spacecraft:
- Pioneer 10, 11 (1973,74)
- Voyager 1,2 Grand Tours (1977…)
- Galileo (Jupiter orbiter + atmospheric probe. 1995)
- Cassini-Huygens (orbiter/probe, arrive Saturn 2004)

**Terrestrial vs. Giant - Size & Density**

**Composition of Atmospheres**
- By number of atoms/molecules

<table>
<thead>
<tr>
<th></th>
<th>Jupiter</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
<th>Outer Solar System Total</th>
<th>Sun</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2</td>
<td>90%</td>
<td>97%</td>
<td>83%</td>
<td>74%</td>
<td>93%</td>
<td>86%</td>
</tr>
<tr>
<td>He</td>
<td>10</td>
<td>3</td>
<td>15</td>
<td>25</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>CH4</td>
<td>0.2</td>
<td>0.2</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Determining the interior structure

- Jupiter ~3x more massive than Saturn, but only slightly larger.
  - Greater pressure $\Rightarrow$ greater density $\Rightarrow$ changes in state of atoms, molecules.
  - For objects 3x more massive than Jupiter, increasing $M \Rightarrow$ decreasing $R$.
  - Sun is larger than Jupiter because it has an internal energy source to heat it up.

  Spherical shell of matter:
  - Acts as if all mass at central point.

  Oblate shell: does not.

- Can use orbits of moons, spacecraft to determine oblateness
  - depends in turn on internal structure, rigidity
Implies gas giants have dense cores

• thick “soup” of rocks and ices
• inner 20-25% of radii
• 15 earth masses for Jupiter,
• 13 for Saturn, Uranus & Neptune.
• So core makes up much of planet for Uranus & Neptune.

Temperature Structure of the Early Solar Nebula

Zone where Hydrogen acts like a metal.
Jupiter

- Main constituents of gaseous atmosphere:
  - Hydrogen: 90%
  - Helium: 10%
  - Methane (CH₄): 0.2%
  - Ammonia (NH₃): 0.02%

- Clouds
  - Frozen ammonia
  - Cause of different colors is unknown

Rotating Jupiter

Atmospheric Structure

Cloud layers, in the Hydrogen-Helium atmosphere.

Ammonia

Water

[Fig 10.11]
Strong winds, differential rotation

- Different than Earth
  - Fast spin
  - Absence of solid surface underneath.

Jupiter: The Great Red Spot

Long-lasting storm, first seen by Galileo in 1610.

Color-coded image, showing which light is reflected off which type of clouds. Uses spectroscopy.
Blue = low clouds
Pink = high, thin clouds
White = high, thick clouds

This is a dynamic, evolving storm:
Movie red spot storm
Galileo mission to Jupiter (1995)

- Orbiter, still studying Jupiter’s moons.
- Probe, parachuted into atmosphere
  - Studied, as function of altitude:
    - Penetration of sunlight
    - Temperature
    - Winds
    - Cloud chemistry
    - Atmospheric composition
Jupiter’s heat sources

- 50% is from solar energy
- But other 50% comes from internal heating
  - This is gravitational energy released when Jupiter formed.
  - Currently stored in interior as heat energy.
  - Slowly being radiated away.
  - Plus maybe some continuing energy release from contraction.
- Similar effect in Saturn
  - But additional effect of same magnitude from ongoing differentiation.
    - Separation of H from He.

There’s weather on Saturn, too...
Uranus

View from Voyager 2, in 1986

False-color image emphasizing “Dark Spot”

Seasons of Uranus
84-year Sidereal Period

[Fig 10.6]

Dark spot due to seasonal heating
### Atmospheres

<table>
<thead>
<tr>
<th></th>
<th>Jupiter</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
<th>Outer Solar System Total</th>
<th>Sun</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>90%</td>
<td>97%</td>
<td>83%</td>
<td>74%</td>
<td>93%</td>
<td>86%</td>
</tr>
<tr>
<td>He</td>
<td>10</td>
<td>3</td>
<td>15</td>
<td>25</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.2</td>
<td>0.2</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Methane

[Fig 10.11]

Methane Clouds on Neptune

Blue color is due to methane (CH₄) gas.

White clouds are methane ice crystals, ~70 km above denser part of atmosphere.

Taken by Voyager 2 from a distance of 590,000 km.
Neptune’s Great Dark Spot

- Anti-cyclone similar to Great Red Spot on Jupiter.
- About same size as Earth.
- Moved across Neptune’s surface at 700 km/hr.
- Seen by Voyager (1989), then disappeared.

Some planets and moons shown in correct relative sizes

Earth

Venus

Mars

Ganymede

Titan

Mercury

Callisto

Io

Moon

Europa

Triton

Pluto

Planets: orbit around Sun

Moons: orbit around planets
The Moons of Jupiter
28 known satellites
– a miniature Solar System

<table>
<thead>
<tr>
<th>Diameter (Moon=1)</th>
<th>Mass (Moon=1)</th>
<th>Semi-major axis (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Callisto</td>
<td>1.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Ganymede</td>
<td>1.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Europa</td>
<td>0.9</td>
<td>0.7</td>
</tr>
<tr>
<td>Io</td>
<td>1.0</td>
<td>1.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Diameter (km)</th>
<th>Relative Density</th>
<th>Density (g/cm^3)</th>
<th>% Reflectivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moon</td>
<td>3476</td>
<td>1.0</td>
<td>3.3</td>
</tr>
<tr>
<td>Callisto</td>
<td>4820</td>
<td>1.5</td>
<td>1.8</td>
</tr>
<tr>
<td>Ganymede</td>
<td>5270</td>
<td>2.0</td>
<td>1.9</td>
</tr>
<tr>
<td>Europa</td>
<td>3130</td>
<td>0.7</td>
<td>3.0</td>
</tr>
<tr>
<td>Io</td>
<td>3640</td>
<td>1.2</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Callisto
• Orbital period: 17 days
• Tidal locking with Jupiter
• Surface temperature = -140° C
  • appears to be mostly ice.
  • 1.8 x density of water
• Many impact craters.
• Not well differentiated
  • Close Galileo flybys ➔ gravitational field ➔ no dense core.
• Geologically dead for 4 billion yrs.
Zooming in on Callisto

Ganymede

- Largest satellite in Solar System
- Fewer impact craters than Callisto ➔ geologically active.
- Differentiated
  - Rock, metal core.
  - Magnetic field present.
- Mantle, crust made of ice
  - Volcanic flows, but water rather than lava.
  - Ridges, valleys due to compression of crust.
- Ganymede is closer to Jupiter than is Callisto
  - Tidal forces may drive this geological activity.
Europa

- *Not* made of ice.
  - Density similar to Moon
- Heating by Jupiter probably the reason.
- Tidal forces keep it geologically active.
- But covered by layer of water ice.
  - Appears to be “pack ice” on top of an ocean.
  - Water must be warmed by heat from Europa’s interior.

Europa’s surface

- Ice rafts
- Nebraska-sized area showing ice and channels
- + the occasional impact crater
- Ice flow cutting across ridge
Io

- Closest to Jupiter (of Galilean Satellites)
  - Strongest tidal forces.
- Active volcanoes
  - hot silicate lava, similar to Earth.

Volcano on Io

Io in Rotation/Volcanoes Erupting
More Io

Images of same region, 5 months apart.

Haemus Mons -
a volcanic cone

Loki Patera
Thought to be a liquid sulphur lake with a solid sulphur raft.

Landscapes on the Galilean Satellites

To Jupiter
### The Innermost Moons of Jupiter

All are tidally locked to Jupiter.

<table>
<thead>
<tr>
<th></th>
<th>Metis</th>
<th>Adrastea</th>
<th>Amalthea</th>
<th>Thebe</th>
<th>(Io)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (km)</td>
<td>40</td>
<td>20</td>
<td>270x166x150</td>
<td>116</td>
<td>3630</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>$10^{17}$</td>
<td>$2 \times 10^{16}$</td>
<td>$7 \times 10^{18}$</td>
<td>$7 \times 10^{17}$</td>
<td>$9 \times 10^{22}$</td>
</tr>
<tr>
<td>Orbit radius (km)</td>
<td>128,000</td>
<td>129,000</td>
<td>181,000</td>
<td>222,000</td>
<td>422,000</td>
</tr>
</tbody>
</table>

Inside Jupiter’s “Roche limit.”

### The Roche limit

- For an extended body in orbit around another body:
  - $P^2 = a^3$ ➔ different parts of extended body have different orbital periods.
  - So body tends to be torn apart.
  - But self-gravity tends to hold it together.
- Roche’s limit is where these two opposing effects are balanced:
  \[
  R_{\text{Roche}} = 2.5 \left( \frac{\rho_{\text{planet}}}{\rho_{\text{moon}}} \right)^{1/3} R_{\text{planet}}
  \]
  where $\rho = \text{mean density}$.
  $R_{\text{planet}} = \text{radius of planet}$.
- Expressed in terms of density and $R_{\text{planet}}$ in order to cancel out terms referring to size and mass of moon and mass of planet.

Galileo flyby… Nov. 5, 2002

Amalthea & Io
...and Jupiter’s outer satellites

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Semimajor Axis (km x 1000)</th>
<th>Diameter (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metis</td>
<td>128</td>
<td>20</td>
</tr>
<tr>
<td>Adrastea</td>
<td>129</td>
<td>40</td>
</tr>
<tr>
<td>Amalthea</td>
<td>181</td>
<td>200</td>
</tr>
<tr>
<td>Thebe</td>
<td>222</td>
<td>90</td>
</tr>
<tr>
<td>Io</td>
<td>422</td>
<td>3630</td>
</tr>
<tr>
<td>Europa</td>
<td>671</td>
<td>3138</td>
</tr>
<tr>
<td>Ganymede</td>
<td>1070</td>
<td>5262</td>
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<tr>
<td>Callisto</td>
<td>1883</td>
<td>4800</td>
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<tr>
<td>Leda</td>
<td>11090</td>
<td>15</td>
</tr>
<tr>
<td>Himalia</td>
<td>11480</td>
<td>180</td>
</tr>
<tr>
<td>Lysithea</td>
<td>11720</td>
<td>40</td>
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<tr>
<td>Elara</td>
<td>11740</td>
<td>80</td>
</tr>
<tr>
<td>Ananke</td>
<td>21200</td>
<td>30</td>
</tr>
<tr>
<td>Carme</td>
<td>22600</td>
<td>40</td>
</tr>
<tr>
<td>Pasiphae</td>
<td>23500</td>
<td>40</td>
</tr>
<tr>
<td>Sinope</td>
<td>23700</td>
<td>40</td>
</tr>
</tbody>
</table>

Captured asteroids?  
Why in two groups??

The Saturn System

5 Moons > 1000 km diameter
+ 26 minor moons.

Rings? What rings?
Saturn’s satellites

Some planets and moons shown in correct relative sizes
Titan

In visible light, from Voyager

• Composition: half ice, half rock.
• Has an atmosphere, with many similarities to Earth’s.

Titan’s atmosphere

[Fig 11.2]

• Density about same as Earth’s
  • 1.6 bars at surface
• Primarily N₂, but also:
  • carbon monoxide (CO)
  • methane (CH₄)
  • ethane (C₂H₆)
  • propane (C₃H₈)
  • hydrogen cyanide (HCN)
    • a building block of DNA
  • C₂N₂, HC₃N
• Thick photochemical smog obscures surface.
• Surface temp = -180° C
What little we know about Titan’s surface

- Infrared images showing 4 faces of Titan
  - From HST
  - See through the haze.

- Titan is tidally locked to Saturn

- Solid brick-red shows regions that could not be imaged through the haze.

Thought to have land masses and ethane oceans

Cassini’s trip to Saturn

Will drop Huygens probe down to Titan’s surface
The other 5 major moons of Saturn

- Tethys
- Dione
- Iapetus
- Rhea
- Enceladus

Saturn’s rings, top & bottom

- 70,000 km wide, only 20m thick!

Bottom view, showing the light that is not reflected by the rings.

Color-enhanced top view, showing “spokes”, of unknown origin.

The Spoke Show
Saturn's Satellites and Ring Structure

Saturn is at 20

Titan is at 20

Roche’s limit and the Rings

Large objects cannot form in this region,
or get broken up even if they do form.
Satellite-Ring Interactions

- Many small satellites none-the-less found in rings.
- Their gravitational interaction shapes the rings:
  - Cause gaps in rings.
  - Swept out through gravitational resonances
    - cf. Orbital periods with 2:1 or 3:2 ratios, etc.
    - or small moons move directly in gaps.
  - Keep rings from spreading out and dissipating
    - Shepherd moons: contain material in rings immediately adjacent to orbit of moon.

What are the rings made of?
- Ice
- + a pinch of dust.

Dynamic Ephemeral Bodies

Rings only 1 km thick

View from Pandora (one of the "shepherd" satellites, including the "braided" F ring)
All 4 Jovian planets have rings

Jupiter’s ring
Imaged by Galileo probe

Uranus
[Fig 11.20]

Neptune
[Fig 11.21]

Triton - the largest moon of Neptune

- 2700 km diameter (0.8 x Moon)
- Probably 75% rock, 25% ice.
- N₂ atmosphere
- Retrograde orbit
- Rotation axis tilted 157° from Neptune’s axis.
- Many similarities to Pluto.
An erupting ice volcano on Triton

Volcanic plume
- rises 8 km above surface
- extends 140 km downwind.
- due to sunlight thawing surface.

Voyager picture

Some planets and moons shown in correct relative sizes

Planets: orbit around Sun
Moons: orbit around planets
Our best images of Pluto:

- **Charon**
  - discovered in 1978
  - half the size of Pluto
  - Pluto previously thought to be much larger.

- Pluto & Charon both in synchronous rotation
  - always show same faces to each other

- Pluto’s inclination = 118° (i.e. tipped on its side)
  - but Charon orbits in Pluto’s equatorial plane.

- Pluto’s orbit crosses Neptune’s
  - Triton has retrograde rotation, etc.
  - *Is there a connection??*

---

**NO**

- Z component of each planet’s position plotted against simultaneous distance from Sun.

  - Pluto’s orbit relative to Neptune, projected into plane of solar system.
  - Pluto’s weird path is due to 3:2 resonance with Neptune.