Lecture 24: Saturn

The Solar System

- First we focus on solar distance, average density, and mass:

<table>
<thead>
<tr>
<th>Planet</th>
<th>Distance to Sun</th>
<th>Density</th>
<th>Mass (Earth units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.4</td>
<td>1.0</td>
<td>0.06</td>
</tr>
<tr>
<td>Venus</td>
<td>0.7</td>
<td>0.9</td>
<td>0.8</td>
</tr>
<tr>
<td>Earth</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Mars</td>
<td>1.5</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>(asteroid)</td>
<td>2.8</td>
<td>0.5</td>
<td>0.0002</td>
</tr>
<tr>
<td>Jupiter</td>
<td>5.2</td>
<td>0.2</td>
<td>318</td>
</tr>
<tr>
<td>Saturn</td>
<td>9.5</td>
<td>0.1</td>
<td>95</td>
</tr>
<tr>
<td>Uranus</td>
<td>19.2</td>
<td>0.2</td>
<td>15</td>
</tr>
<tr>
<td>Neptune</td>
<td>30.1</td>
<td>0.3</td>
<td>17</td>
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<tr>
<td>Pluto</td>
<td>39.5</td>
<td>0.3</td>
<td>0.003</td>
</tr>
</tbody>
</table>

(where we have used Earth units)

Saturn's Rings

- Fache gap
- A ring
- Cassini Division
- B ring
- C ring
The Solar System

Saturn’s Orbit

The period of Saturn’s orbit is $P = 29.5$ Earth years

Kepler’s third law relates the semi-major axis $a$ to the orbital period $P$

$$ \left( \frac{P}{\text{years}} \right)^2 = \left( \frac{a}{\text{AU}} \right)^3 $$

Solving for the semi-major axis $a$ yields

$$ \left( \frac{a}{\text{AU}} \right) = \left( \frac{P}{\text{years}} \right)^{2/3} $$

Since $P = 29.5$ Earth years, we obtain $a = 9.54$ AU

Saturn’s orbit has eccentricity $e = 0.056$
Saturn’s Orbit

- The distance from the Sun varies by about 10% during an orbit
  - \( D_{\text{perihelion}} = 9.01 \text{ AU} \)
  - \( D_{\text{aphelion}} = 10.08 \text{ AU} \)

- Like Mars and Jupiter, Saturn is easiest to observe during favorable opposition.
  - At this time, the Earth-Saturn distance is only about 8 AU.

Saturn’s Orbit

- It is best to observe Saturn during favorable opposition because:
  - It displays the full phase.
  - It is at minimum distance from Earth.
  - It is at minimum distance from the Sun.
  - It has largest angular size and is brightest.

Bulk Properties of Saturn

- Saturn is the second largest planet in the solar system.
- We have for the radius and mass of Saturn:
  - \( R_{\text{Saturn}} = 60,000 \text{ km} = 9.4 \ R_{\text{Earth}} \)
  - \( M_{\text{Saturn}} = 5.6 \times 10^{29} \text{ g} = 95 \ M_{\text{Earth}} \)
- The volume of Saturn is therefore given by:
  \[
  V_{\text{Saturn}} = \frac{4}{3} \pi R_{\text{Saturn}}^3
  \]
- Hence \( V_{\text{Saturn}} = 9 \times 10^{29} \text{ cm}^3 \)
**Bulk Properties of Saturn**

- The average density of Saturn is therefore

\[ \rho_{\text{saturn}} = \frac{M_{\text{saturn}}}{V_{\text{saturn}}} = \frac{5.6 \times 10^{25} \text{g}}{9 \times 10^{29} \text{cm}^3} \]

- We obtain

\[ \rho_{\text{saturn}} = 0.62 \text{ g cm}^{-3} \]

- Hence there is little if any iron and no dense core inside Saturn
- Saturn is composed mostly of hydrogen gas
- It has a relatively small, rocky core

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**Saturn’s Rotation**

- Is there any way to find a single, meaningful rotation period for the entire planet?

- The rotation period is different for clouds in bands A, B, and C
- Like Jupiter, Saturn displays differential rotation
- The strong magnetic field indicates that the rotation period of the core is about 10 hours, which is close to Jupiter’s spin period
- The fast rotation drives powerful winds and storms

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**Auroras on Saturn**
Differential (shear) rotation drives storms on Saturn
Saturn’s Rotation

- The rapid rotation produces a strong Coriolis force and a significant equatorial bulge
- However, Saturn has a spin axis tilt of 27°, which is much larger than the 3° tilt for Jupiter
- This causes somewhat different weather and band patterns on Saturn
- The tilt of the axis also causes us to view Saturn’s rings from various angles during Saturn’s orbit

Saturn’s Atmosphere

- Atmospheric composition:
  - H₂ -- 92.4%
  - He -- 7.4%
  - CH₄ -- 0.2%
  - NH₃ -- 0.02%
  - H₂O - trace
  - Water ice clouds
  - Ammonia ice clouds
- Like Jupiter, Saturn was able to retain its primary atmosphere
- The two planets probably started out with very similar atmospheric compositions

Saturn and Jupiter

- If Jupiter and Saturn have the same overall composition, why is Jupiter more dense?
- Probably because Jupiter is more massive and has a rockier core (Saturn’s core contains some ice which lowers the density)
  \[
  \rho_{\text{saturn}} = 0.62 \ \text{g cm}^{-3}
  \]
  \[
  \rho_{\text{jupiter}} = 1.24 \ \text{g cm}^{-3}
  \]
Saturn's Atmosphere

- Why are the atmospheric compositions so different now?
- We need to examine the structure of Saturn's atmosphere

Surface Gravity

- Using values for the Earth, Moon, Jupiter, and Saturn, we obtain for the surface accelerations

\[
\begin{align*}
A_{\text{Earth}} &= -\frac{GM_{\text{Earth}}}{R_{\text{Earth}}^2} = 9.8 \text{ m s}^{-2} \\
A_{\text{Moon}} &= -\frac{GM_{\text{Moon}}}{R_{\text{Moon}}^2} = 1.7 \text{ m s}^{-2} \\
A_{\text{Jupiter}} &= -\frac{GM_{\text{Jupiter}}}{R_{\text{Jupiter}}^2} = 24.9 \text{ m s}^{-2} \\
A_{\text{Saturn}} &= -\frac{GM_{\text{Saturn}}}{R_{\text{Saturn}}^2} = 10.38 \text{ m s}^{-2}
\end{align*}
\]

- The acceleration at the cloud level on Saturn is close to that on the Earth's surface

Saturn's Atmosphere

- Because Saturn has a lower surface gravity at the cloud level, its cloud deck is thicker (200 km) than Jupiter's (80 km)
- This allows us to see the colorful, underlying layers more easily in Jupiter's atmosphere
- The temperature at the cloud tops on Saturn is 97 K
- The predicted equilibrium temperature at Saturn's distance from the Sun is 73 K
- Therefore, Saturn radiates about three times more energy than it receives from the Sun
Saturn's Atmosphere

- As with Jupiter, heating due to the radioactive decay of heavy elements is not strong enough to explain the observed temperature of Saturn.
- Saturn is too small to have retained its heat of formation.
- We think that Saturn is still experiencing internal differentiation as dense material sinks towards the center.
- Saturn's atmosphere is so cold that helium can condense and "rain" down into the deep interior (Jupiter is too warm for this to happen).

Hydrogen gas
Helium gas
Helium droplets

Saturn's Atmosphere

- The ongoing differentiation causes the interior to heat up.
- The heating occurs when kinetic energy is converted into thermal energy.
- The helium droplets fall with high speed into the interior.
- When they bump into other droplets, it causes heating.

Saturn's Atmosphere

- The helium rain phenomenon explains:
  - the observed depletion of helium in Saturn’s atmosphere (relative to Jupiter's)
  - the extra heat produced by Saturn.

Saturn's atmosphere:
- \( \text{H}_2 \) -- 92.4%
- \( \text{He} \) -- 7.4%
- \( \text{CH}_4 \) -- 0.2%
- \( \text{NH}_3 \) -- 0.02%
- \( \text{H}_2\text{O} \) -- trace
- Water ice clouds
- Ammonia ice clouds

Jupiter's Atmosphere:
- \( \text{H}_2 \) -- 86.1%
- \( \text{He} \) -- 13.8%
- \( \text{CH}_4 \) -- trace
- \( \text{NH}_3 \) -- trace
- \( \text{H}_2\text{O} \) -- trace
- Water ice clouds
- Ammonia ice clouds
Interior of Saturn

- With a radius of 60,000 km and thickness of 200 km, the atmosphere is mostly molecular hydrogen gas, H₂.
- A huge shell of metallic hydrogen under great pressure exists below a radius of 30,000 km.
- Farther inside lies the icy, rocky core, with a radius of about 15,000 km.

Saturn’s interior

- Molecular hydrogen
- Radius 15,000 km
  - Temperature: 15,000 K
  - Pressure: 5 x 10⁸ atm
- Radius 30,000 km
  - Temperature: 8000 K
  - Pressure: 3 x 10⁸ atm
- Radius 60,000 km
  - Temperature: 260 K
  - Pressure: 10 atm
- Icy/rocky core

Jupiter’s interior

- Molecular hydrogen
- Depth 100 km
  - Temperature: 300 K
  - Pressure: 10 atm
- Depth 20,000 km
  - Temperature: 11,000 K
  - Pressure: 3 x 10⁶ atm
- Depth 60,000 km
  - Temperature: 28,000 K
  - Pressure: 12 x 10⁷ atm
- Depth 70,000 km
  - Temperature: 40,000 K
  - Pressure: 53 x 10⁷ atm
Saturn’s Rings

• In 1857, James Clerk Maxwell showed that Saturn’s rings cannot be solid, liquid, or gas
• Therefore, they must be composed of many small objects, all independently orbiting Saturn
• This was confirmed in 1895 when the Doppler shift of sunlight reflected from the particles was measured

Saturn’s Rings

• The albedo of the ring particles is about 0.8, suggesting an icy composition – the ring particles are “snowballs”
• The thickness of the rings is only 20-30 meters, while the radius is about 100,000 km – the rings are VERY thin
• The thinness is maintained by particle-particle collisions and interactions with Saturn’s moons

Saturn’s Rings

• Inside the Roche limit, the tidal force of Saturn overwhelms the self-gravity of a moon, ripping it apart
• The rings may exist due to the breakup of one or more small moons that passed inside Saturn’s Roche limit
The structure of the rings is VERY complex. We observe:
- Spiral density waves
- Many gaps
- Braided rings
- Shepherd satellites
- Transient spokes
Braided F-ring

Shepherd satellites movie

Shepherd satellites
Saturn’s Rings

- The numerous gaps in the rings are caused by resonances with the various satellites of Saturn
- For example, the Cassini division is due to a 2:1 resonance with Saturn’s innermost major moon, Mimas

Saturn's Ring Structure

Ring gaps
Saturn’s Rings

• The Cassini division is in a 2:1 resonance with Mimas
• The outer edge of the A ring is in a 7:6 resonance with Janus
• The Encke gap is in a 5:3 resonance with Mimas

Saturn’s Moons

• Currently 46 natural satellites of Saturn have been discovered
• They are primarily composed of ice, most with an average density of about 1 g cm\(^{-3}\)
• The largest moon is Titan, which is 5,150 km in diameter, and has a density of 1.9 g cm\(^{-3}\)
• Titan is unique among moons in that it possesses an atmosphere
• The moon has a distinctly reddish color due to its atmospheric composition

 transient spokes

Saturn’s moons webpage
Primary Moons in the Solar System

- Ganymede: 5262 km
- Titan: 5150 km
- Mercury: 4880 km
- Callisto: 4806 km

- Io: 3642 km
- Moon: 3476 km
- Europa: 3138 km
- Triton: 2706 km
- Pluto: 2305 km
- Titan: 1580 km

The Largest Moons and Smallest Planets

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Saturn with moons Rhea and Dione

Rhea's icy, cratered surface

Cassini Mission at Saturn & Titan
Saturn with moon Titan

Titan’s Atmosphere

- Titan has a reddish color due to its atmospheric composition
  - N 90%
  - Ar 7%
  - CH₄ 3%
- Titan’s atmosphere acts like a solar-powered chemical factory
- Many hydrocarbon compounds are probably present on the surface
- There may be methane snow and rain, and oceans of ethane
- Surface pressure is 60% greater than Earth’s, surface temperature is 97 K (the equilibrium temperature)
- Is life possible there?

Huygens video 1  Huygens video 2  Huygens video 3
Titan's Atmosphere

- Why does Titan have a dense atmosphere, when none of the other moons do?
- At its large distance from the Sun, Titan was much colder, and able to retain its methane and ammonia
- Radioactivity warmed the ices to form an atmosphere
- Sunlight split the ammonia (NH₃) into hydrogen and nitrogen, and the hydrogen escaped into space
- The methane remained to form the dense atmosphere we see today