Lecture 25: The Outer Planets

Neptune

Uranus

Pluto/Charon

Uranus and three moons

Neptune and two moons
The Outer Planets

<table>
<thead>
<tr>
<th>Planet</th>
<th>Distance (Earth)</th>
<th>Mass (Earth)</th>
<th>Radius (Earth)</th>
<th>Orbital Period (Earth)</th>
<th>Orbital Inclination (Earth)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mars</td>
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<td>0.05</td>
<td>0.11</td>
<td>0.13</td>
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<td>2.00</td>
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<tr>
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<td>15.00</td>
<td>15.00</td>
<td>0.060</td>
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<td>Neptune</td>
<td>30.57</td>
<td>30.57</td>
<td>20.57</td>
<td>20.57</td>
<td>0.070</td>
</tr>
</tbody>
</table>

*Discovered by William Herschel in 1781, who realized that this extended object was not a star.*

**Uranus**

- The first new planet discovered in 2000 years, and the first to lie beyond the "classical" planets Mercury, Venus, Earth, Mars, Jupiter, and Saturn.
- It is barely bright enough to be seen without a telescope.
Uranus

- The orbit of Uranus has eccentricity \( e = 0.0461 \)
- The distance from the Sun varies by about 10% during an orbit
  - \( D_{\text{perihelion}} = 18.3 \) AU
  - \( D_{\text{aphelion}} = 20.1 \) AU
- Kepler’s third law relates the semi-major axis \( a \) to the orbital period \( P \)

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

- Observations show that \( P = 84.1 \) Earth years for Uranus, and therefore we obtain \( a = 19.2 \) AU

Discovery of Neptune

- Surprisingly, the orbit of Uranus turns out not to be exactly elliptical – in 50 years the discrepancy grew to about 15 arc seconds
- Does this suggest that there is something wrong with Kepler’s laws?
- Or, is some other force at work, in addition to the Sun’s gravity?

- In 1845-6, two mathematicians independently deduced that another body must be causing the anomaly
- This led to the prediction of the location of an eight planet
- It was discovered late in 1846, only one or two degrees from the predicted location!
- The mathematicians got credit for the discovery – not the astronomer!
- The newly discovered planet was named Neptune
Neptune
- The orbit of Neptune has eccentricity $e = 0.01$
- The distance from the Sun varies by about 2% during an orbit
  - $D_{\text{perihelion}} = 29.8$ AU
  - $D_{\text{aphelion}} = 30.4$ AU
- Kepler’s third law relates the semi-major axis $a$ to the orbital period $P$
  \[
  \frac{P}{\text{years}} = \frac{a^{3/2}}{\text{AU}}
  \]
- Observations of the parallax of Neptune show that $a = 30.1$ AU, and therefore we obtain $P = 164$ Earth years
- Since its discovery in 1846, 157 years have passed and Neptune has almost completed one orbit around the Sun

Discovery of Pluto
- Remaining problems with the orbits of Uranus and Neptune suggested that there may be a ninth planet perturbing their orbits...
- Percival Lowell used theoretical calculations to predict the mass and location of a ninth planet in 1906
- About 14 years after Lowell died, in 1930, Pluto was discovered by Clyde Tombaugh only 6 degrees from the predicted location!
- However, it turns out that there were no real problems with the orbits of Uranus and Neptune, and therefore the discovery of Pluto was just a coincidence!

Pluto’s Orbit
- The orbit of Pluto has eccentricity $e = 0.25$, the largest for any planet in the solar system
- The distance from the Sun varies by about 50% during an orbit
  - $D_{\text{perihelion}} = 29.7$ AU
  - $D_{\text{aphelion}} = 49.3$ AU
- Kepler’s third law relates the semi-major axis $a$ to the orbital period $P$
  \[
  \frac{P}{\text{years}} = \frac{a^{3/2}}{\text{AU}}
  \]
- Observations of the parallax of Pluto show that $a = 39.5$ AU, and therefore we obtain $P = 248$ Earth years
- Since its discovery in 1930, Pluto has completed only about 30% of one orbit around the Sun
Pluto and Neptune

- Note that for Pluto,
  - $D_{\text{perihelion}} = 29.7$ AU
  - $D_{\text{aphelion}} = 49.3$ AU
- Note that for Neptune,
  - $D_{\text{perihelion}} = 29.8$ AU
  - $D_{\text{aphelion}} = 30.4$ AU
- Hence during part of the time, Pluto is actually the 8th planet from the Sun and Neptune is the 9th planet!
- This means that Pluto and Neptune can get fairly close together, suggesting
  - A possible orbital resonance between them
  - Perhaps Pluto is an escaped moon of Neptune

Following up on the orbital resonance possibility, we note that
- $P_{\text{pluto}} = 248$ Earth years
- $P_{\text{neptune}} = 164$ Earth years
- Hence we find that
  \[ 2 \times P_{\text{pluto}} = 3 \times P_{\text{neptune}} \]
- It therefore appears that the two planets are locked in a 2:3 orbital resonance!
- The resonance is enforced by the close approaches which happen every few hundred years
Bulk Properties of the Outer Planets

- The radii are given by
  - $R_{\text{Uranus}} = 24,750 \text{ km} = 4.0 \, R_{\text{Earth}}$
  - $R_{\text{Neptune}} = 25,550 \text{ km} = 3.9 \, R_{\text{Earth}}$
  - $R_{\text{Pluto}} = 1,150 \text{ km} = 0.2 \, R_{\text{Earth}}$

- The masses are given by
  - $M_{\text{Uranus}} = 8.7 \times 10^{28} \text{ g} = 14.6 \, M_{\text{Earth}}$
  - $M_{\text{Neptune}} = 1.0 \times 10^{29} \text{ g} = 17.2 \, M_{\text{Earth}}$
  - $M_{\text{Pluto}} = 1.5 \times 10^{25} \text{ g} = 0.0025 \, M_{\text{Earth}}$

- The average densities are given by
  - $\rho_{\text{Uranus}} = 1.2 \text{ g cm}^{-3}$
  - $\rho_{\text{Neptune}} = 1.7 \text{ g cm}^{-3}$
  - $\rho_{\text{Pluto}} = 2.0 \text{ g cm}^{-3}$

Bulk Properties of the Outer Planets

- The average densities of Uranus and Neptune are similar to Jupiter’s (1.2 g cm$^{-3}$) and higher than Saturn’s (0.6 g cm$^{-3}$)
- Neptune and Uranus probably have large rocky cores
- They also have a metallic hydrogen layer, as well as a deeper layer of ionized ammonia “slush”, where the magnetic field is formed
- Pluto is composed of rock and ice, with a surface temperature of 50 K

Rotation Rates

- The rotation period of Uranus is 17.2 hours according to magnetic field measurements - the spin axis is tilted by 98° (it is almost perpendicular to the orbital axis)...is this due to a collision??
- The rotation period of Neptune is 16.1 hours according to observations of the magnetic field, and the tilt of Neptune’s spin axis is 29.6°
- Pluto has a spin period of 6.4 Earth days, and a spin axis tilt of 120° -- it is tidally locked to its moon, Charon
Atmospheric Compositions

• Uranus’s Atmosphere:
  - H₂ -- 84%
  - He -- 14%
  - CH₄ -- 2%
  - NH₃ -- freezes
  - The cloud-top temperatures on Uranus and Neptune are around 58-59 K, which is below the freezing point of ammonia gas.
  - These temperatures are close to the predicted equilibrium value (no heat source required)
  - The methane gas (CH₄) absorbs the red light, making the planets appear blue in color.
  - Neptune’s atmosphere is similar in composition to Uranus’s, except that there is 3% methane, giving it a more blue appearance.
  - Pluto has a very thin methane atmosphere - with methane snow!

• Jupiter’s Atmosphere:
  - H₂ -- 86.1%
  - He -- 13.8%
  - CH₄ -- trace
  - NH₃ -- trace

Voyager 2, January 10, 1986
Neptune's atmosphere

36 hours in Neptune's atmosphere
Clouds on Neptune

Internal Structures

- Jupiter, Saturn, Uranus, and Neptune have strong magnetic fields, powered by the fast rotation.
- The magnetic fields on Jupiter and Saturn are centered close to the core of each planet, and are probably produced in the metallic hydrogen layers.
- The magnetic fields on Neptune and Uranus are quite offset from the core of each planet, and display very large tilt angles.
Formation of Ring Systems

- Jupiter, Saturn, Uranus, and Neptune all have ring systems.
- The rings exist inside the Roche limit, the tidal force of the planet 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 the Roche limit.
- It is not clear why Saturn’s ring system is the most extensive – it may only last a few million years before dissipating.
Rings of Uranus

- The ring system of Uranus was discovered using stellar occultation, when the rings move in front of a background star.
Moons of Uranus

- Uranus has at least 22 moons
- The primary satellites are:

<table>
<thead>
<tr>
<th>Name</th>
<th>Distance</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miranda</td>
<td>5.09</td>
<td>1.3 g/cm³</td>
</tr>
<tr>
<td>Ariel</td>
<td>7.48</td>
<td>1.6 g/cm³</td>
</tr>
<tr>
<td>Umbriel</td>
<td>10.4</td>
<td>1.4 g/cm³</td>
</tr>
<tr>
<td>Titania</td>
<td>17.1</td>
<td>1.6 g/cm³</td>
</tr>
<tr>
<td>Oberon</td>
<td>22.8</td>
<td>1.5 g/cm³</td>
</tr>
</tbody>
</table>

- Here, the distances are in units of the planet’s radius
- Most are relatively small and icy/rocky in composition
- They are heavily cratered
- These satellites are similar to the moons of Saturn

Miranda

- Miranda has a unique surface with many different geological features...
- The great variety of terrain suggests a very violent history
Uranus's moon Miranda
# Moons of Neptune

- Neptune has at least 8 moons.
- The primary satellites are:

<table>
<thead>
<tr>
<th>Name</th>
<th>Distance</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triton</td>
<td>14.3</td>
<td>2.1 g/cm³</td>
</tr>
<tr>
<td>Nereid</td>
<td>223</td>
<td>2.0 g/cm³</td>
</tr>
</tbody>
</table>

- Here, the distances are in units of the planet's radius.
- They are heavily cratered.
- They are relatively small and icy/rocky in composition.
- Triton is the largest, with a radius of 1,350 km.
- The densities of 2 g/cm³ suggest a rockier composition than most of the other outer moons - quite similar to Pluto.

- Triton orbits in a retrograde direction, perhaps indicating that it is a captured satellite.

*Hubble image of Triton and Neptune*
Pluto and Charon

- Pluto's orbit has an eccentricity $e = 0.25$ and it is tilted by $17^\circ$ relative to the ecliptic plane.
- Surprisingly, Pluto has its own small satellite, called Charon, discovered in 1978.
- Charon is 1/6 as massive as Pluto, which is the largest ratio for any moon and planet in the solar system.

1978 photo showing discovery of Charon

Pluto - Hubble Optical Telescope

Hubble image of Pluto and Charon
Hubble images of Pluto
We are not sure how the Pluto-Charon system formed.

- The orbit of Charon is tilted by 118° relative to Pluto's orbit.
- This causes the two objects to occult each other as viewed from Earth, every 124 years.

Pluto and Charon

The duration of the occultations allows a precise measurement of the radii of both objects. Combining this information with Newton's laws allows the determination of the size, mass, and density of both objects. The densities of each are close to 2 g/cm³, which is similar to Triton.
Mysteries of the Outer Planets

- Why does Saturn have a spectacular ring?
- Could life exist on Saturn's moon Titan?
- How did Uranus end up so tilted?
- When were the moons of Uranus formed?
- What happened to Miranda to explain its complex surface?
- How could Pluto be an escaped moon of Neptune when it has its own satellite?