Part II: Solar System

Lecture: Planetology

Updated: 2012Feb10

Planetology

A. Structure of Solar System
B. Planetology
C. The Planets and Moons

A. Components of Solar System

1. Planets
2. Minor Planets (Asteroids)
3. Kuiper Belt & Oort Cloud
4. Comets, Meteors

Orbits of Planets

- All orbit in same direction, same as sun rotates, as moon orbits earth, and as most planets rotate.
- Pluto’s orbit goes inside of Neptune’s!

Inclination of Orbits

- All planets lie in the ecliptic plane (except Pluto)
- Mercury’s orbit is also slightly inclined.

Rotational Oddities

- Uranus rotates SIDEWAYS
- Venus rotates BACKWARDS
- Earth, Mars, Saturn are tilted
Titius-Bode Law (1766)

- The distances between the planets gets bigger as you go out.
- Titius & Bode came up with a law that predicted the size of the orbits.
- Big gap between Mars (1.6 AU) & Jupiter (5.2 AU).
- Predict planet at 2.8 AU.
- Neptune does not fit the pattern.

Ceres Discovered 1801

- First asteroid discovered by accident by Piazzi 1801.
- It's the biggest, 950 km in diameter (small compared to moon).
- Contains 32% of mass of entire asteroid belt.
- Combined mass of all asteroids is only 4% of earth’s moon.

A.3: Minor Planets: Asteroids

- Most asteroids orbit the Sun in a belt about 1.5 AU wide between the orbits of Mars and Jupiter.
- Ceres is the biggest, 950 km in diameter (small compared to moon).
- Contains 32% of mass of entire asteroid belt.
- Combined mass of all asteroids is only 4% of earth's moon.

Some Asteroids visited recently

- Asteroid Eros
- Asteroid Gaspra

Kuiper Belt

- Objects Beyond Neptune—The Trans-Neptunian Objects
- Pluto is not a planet anymore.
- It's now classified as a Kuiper Belt Object.
Hubble Space Telescope: Our best image of Pluto

Dermott’s Law

- Neptune does not fit the Titius-Bode law
- Dermott (1960) suggests a power law for orbital periods works better.
  \[ T(n) = T_0 C^n \]
- Further, he shows it works for moons of Jupiter, Saturn and Uranus.
- There is some evidence that Extra-Solar planets may follow this type of law.
- But what is the REASON for there to be any law at all governing the spacing of planetary bodies?

B. Planetology

1. Terrestrial Planets
2. Jovian Planets
3. Moons

Density

Density = mass per unit volume

- \( H_2O = 1 \) (gram/cm\(^3\))
- Rock (typical) = 2.5
- Iron = 7.9
- Lead = 11.4
- Earth = 5.5, has iron core, rocky mantle
- Moon = 3.3, i.e. very little iron, mostly rock
- Jupiter = 1.3, so little rock, mostly Hydrogen

<table>
<thead>
<tr>
<th>Object</th>
<th>Percentage of Total Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>99.90</td>
</tr>
<tr>
<td>Jupiter</td>
<td>0.10</td>
</tr>
<tr>
<td>Comets</td>
<td>0.05</td>
</tr>
<tr>
<td>All other planets</td>
<td>0.04</td>
</tr>
<tr>
<td>Satellites and rings</td>
<td>0.00005</td>
</tr>
<tr>
<td>Asteroids</td>
<td>0.000002</td>
</tr>
<tr>
<td>Cosmic dust</td>
<td>0.00000001</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>Distance from Sun (AU)</th>
<th>Revolutions Period (years)</th>
<th>Diameter (km)</th>
<th>Mass (10^{24} kg)</th>
<th>Density (g/cm(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.39</td>
<td>0.24</td>
<td>4,878</td>
<td>3.3</td>
<td>5.4</td>
</tr>
<tr>
<td>Venus</td>
<td>0.72</td>
<td>0.02</td>
<td>12,102</td>
<td>45.7</td>
<td>3.5</td>
</tr>
<tr>
<td>Earth</td>
<td>1.00</td>
<td>1.00</td>
<td>12,756</td>
<td>58.8</td>
<td>5.5</td>
</tr>
<tr>
<td>Mars</td>
<td>1.52</td>
<td>1.88</td>
<td>6,796</td>
<td>6.4</td>
<td>3.0</td>
</tr>
<tr>
<td>Jupiter</td>
<td>5.20</td>
<td>11.86</td>
<td>142,884</td>
<td>189,011</td>
<td>1.3</td>
</tr>
<tr>
<td>Saturn</td>
<td>9.54</td>
<td>20.46</td>
<td>120,536</td>
<td>5,996</td>
<td>0.7</td>
</tr>
<tr>
<td>Uranus</td>
<td>19.18</td>
<td>84.07</td>
<td>51,113</td>
<td>806</td>
<td>1.3</td>
</tr>
<tr>
<td>Neptune</td>
<td>30.06</td>
<td>164.52</td>
<td>4,090</td>
<td>1,030</td>
<td>1.6</td>
</tr>
<tr>
<td>Pluto</td>
<td>39.44</td>
<td>240.80</td>
<td>2,200</td>
<td>2.00</td>
<td>0.60</td>
</tr>
</tbody>
</table>

*An AU (astronomical unit) is the distance from Earth to the Sun.
We give densities in units where the density of water is 1. To get densities in units of kg/m\(^3\), multiply the value we give by 1000.
Comparing Terrestrial and Jovian

<table>
<thead>
<tr>
<th>Terrestrial Planets</th>
<th>Jovian Planets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from the Sun</td>
<td>Less than 2 AU</td>
</tr>
<tr>
<td>Size</td>
<td>Small</td>
</tr>
<tr>
<td>Composition</td>
<td>Mostly rocky materials containing iron, oxygen, silicon, magnesium, nickel, and sulfur</td>
</tr>
<tr>
<td>Density</td>
<td>High</td>
</tr>
</tbody>
</table>

Note the scale is in POWERS of 10, so Fluorine is 10,000 times less abundant than Carbon (not half as much as you might think at first glance).

The Frost Line

- Distance from (proto)sun where temperature is below 150 K such that hydrogen compounds (water, ammonia) form ice.
- Approximately 2.7 AU from sun. This is dividing line between Terrestrial and Jovian Planets.

Terrestrial Planets Properties

<table>
<thead>
<tr>
<th>Characteristic of the Planets</th>
<th>Terrestrial Planets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>Venus</td>
</tr>
<tr>
<td>Average distance from Sun (AU)</td>
<td>0.387</td>
</tr>
<tr>
<td>Orbital period (years)</td>
<td>0.24</td>
</tr>
<tr>
<td>Rotation axis inclination</td>
<td>0.236</td>
</tr>
<tr>
<td>Equatorial diameter (km)</td>
<td>4,880</td>
</tr>
<tr>
<td>Equatorial circumference (Earth = 1)</td>
<td>1.636</td>
</tr>
<tr>
<td>Mass (Earth = 1)</td>
<td>0.055</td>
</tr>
<tr>
<td>Average density (g/cm³)</td>
<td>5.44</td>
</tr>
</tbody>
</table>

Terrestrial planets have abundances of elements similar to the sun, if you throw away the hydrogen and helium, however they have higher proportions of heavier elements (n.b. iron). For example the earth has:
- 32% Iron
- 30% Oxygen
- 15% Silicon (rock)
- 14% Magnesium

Elements in Sun (Solar System)

Note the scale is in POWERS of 10, so Fluorine is 10,000 times less abundant than Carbon (not half as much as you might think at first glance).

B.1: The Terrestrial (Earth-like) Planets

The earth is “differentiated”
- Inner Core: solid iron
- Outer Core: liquid iron
- Mantle: heavy rock (olivine)
- Crust: light rock (granite)
1b. How did it get this way? **Differentiation!**

Heat came from radioactive decay (e.g. Aluminum 26) and/or intense meteor impacts, heated up interior, heavy stuff sank to center. This releases even more gravitational potential energy!

![Differentiation Diagram](image)

1c. More heat is released as liquid core freezes

Melting point increases with pressure, so the melting point temperature is higher deeper inside the earth. The very center is hence solid.

At current rate, it will take several billion years for entire core to become solid.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Earth (in %)</th>
<th>Venus (in %)</th>
<th>Mars (in %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>0.03</td>
<td>96</td>
<td>95.3</td>
</tr>
<tr>
<td>Nitrogen (N₂)</td>
<td>78.1</td>
<td>3.5</td>
<td>2.7</td>
</tr>
<tr>
<td>Argon (Ar)</td>
<td>0.93</td>
<td>0.006</td>
<td>1.6</td>
</tr>
<tr>
<td>Oxygen (O₃)</td>
<td>21.0</td>
<td>0.003</td>
<td>0.15</td>
</tr>
<tr>
<td>Neon (Ne)</td>
<td>0.002</td>
<td>0.001</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

**Table 9.2 Atmospheric Compositions of Earth, Venus, and Mars**

Magellan Probe (1990): Venus has few craters, young surface

This is what Mars looks like with the Hubble, showing ice cap and clouds

And with a dust storm
Viking 1 (1976): Landing Site

- Large rock ~ 2 meters wide
- Top of rock covered with red soil
- Exposed rock similar in color to basaltic rocks on Earth
- This rock = fragment of lava flow that was later ejected by impact crater?
- Red surface color due to oxidized iron in the eroded material
- Characterized by rocky plains and also small drifts of regolith

Viking 2: Landing Site

- More and larger blocks of stone than Viking 1 site
- Stones are likely ejecta from nearby impact craters
- Many rocks are angular, only slightly altered by wind erosion
- Drifts of sand and dust are small and less noticeable than Viking 1 site
- Pink sky color caused by extremely fine red dust suspended in thin atmosphere

- The heavily cratered southern highlands are older and about 5 km higher in elevation than the smooth northern lowlands
- The origin of this crustal dichotomy is not completely understood

1. Crustal Dichotomy

- The Moon is one-fourth the size of the Earth
- The light gray areas are called highlands – they are heavily cratered and mountainous
- The dark black/gray areas are called maria – they are lightly cratered and relatively smooth

The Moon’s other side

- There are very few maria on the Moon’s far side.
- We’re not sure why.
Giant Impact Theory

- During middle to late stages of Earth's accretion, about 4.5 billion years ago, Mars-sized body impacted Earth.
- The impact ejected Earth's crust and formed Earth's satellite Moon.
- Earth's iron core is about 75% of the planet's diameter, or 42% of its volume.
- Whereas Mercury's iron core is 55% of the diameter of the entire planet, or 17% of its volume.
- Mariner 10 (1973-1975) probe only sees about half of the surface of Mercury.
- Rachmaninoff Basin (250 km) has evidence of recent volcanism, about 1 or 2 billion years ago.

Mariner 10 (1973-1975)

- Mariner 10 only sees about half of Mercury's surface.
- Has a big iron core with little on the surface.

Rachmaninoff Basin (250 km)

- Lack of craters in the inner basin implies volcanism after impact, as recent as 1 or 2 billion years ago.

B.2: The Jovian Planets
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<table>
<thead>
<tr>
<th>The Outer Planets</th>
<th>Jupiter</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
<th>Pluto</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average distance from Sun (AU)</td>
<td>5.2, 5.8</td>
<td>9.57</td>
<td>19.18</td>
<td>30.06</td>
<td>39.53</td>
</tr>
<tr>
<td>Orbital period (years)</td>
<td>11.86</td>
<td>29.46</td>
<td>84.06</td>
<td>164.80</td>
<td>248.50</td>
</tr>
<tr>
<td>Orbital eccentricity</td>
<td>0.046</td>
<td>0.051</td>
<td>0.063</td>
<td>0.093</td>
<td>0.209</td>
</tr>
<tr>
<td>Inclination of orbit to the ecliptic</td>
<td>1.3°</td>
<td>2.5°</td>
<td>0.77°</td>
<td>1.8°</td>
<td>17.1°</td>
</tr>
<tr>
<td>Equatorial diameter (km)</td>
<td>142,984</td>
<td>120,536</td>
<td>51,484</td>
<td>49,248</td>
<td>21,800</td>
</tr>
<tr>
<td>Mass (Earth’s mass)</td>
<td>(1.823 \times 10^27)</td>
<td>(5.681 \times 10^{26})</td>
<td>(5.682 \times 10^{26})</td>
<td>(1.324 \times 10^{26})</td>
<td>(1.33 \times 10^{26})</td>
</tr>
<tr>
<td>Mass (Earth’s mass)</td>
<td>(1.43)</td>
<td>(9.16)</td>
<td>(9.55)</td>
<td>(17.51)</td>
<td>(0.062)</td>
</tr>
<tr>
<td>Average density (g/cm³)</td>
<td>1.324</td>
<td>0.687</td>
<td>0.186</td>
<td>0.148</td>
<td>0.690</td>
</tr>
</tbody>
</table>

Jovian planets are similar in composition to the sun:
- 75% hydrogen
- 24% helium
- 1% other elements (rock, iron)

Terrestrial Planets often have Iron cores, and hence a magnetic field

The Aurora (Northern or Southern Lights)

The aurora arises from the interaction of the solar wind with a planet’s magnetic field

Surprise: Gas Giants show Auroras, hence have magnetic fields, but don’t have iron core (?)

The oblateness of Jupiter and Saturn reveals their rocky cores

- Jupiter probably has a rocky core several times more massive than the Earth
- The core is surrounded by a layer of liquid “ices” (water, ammonia, methane, and associated compounds)
- On top of this is a layer of helium and liquid metallic hydrogen and an outermost layer composed primarily of ordinary hydrogen and helium
- Saturn’s internal structure is similar to that of Jupiter, but its core makes up a larger fraction of its volume and its liquid metallic hydrogen mantle is shallower than that of Jupiter

Jupiter: Storms

- Great Red Spot
  - about size of Earth
  - At largest, has been seen at 3x Earth size
  - Rotates ccw
  - more than 300 yrs old
- White ovals
  - smaller, less long-lived
  - also rotate ccw
The moon's own gravity tends to hold it together.
Tidal forces from planet tend to pull it apart
The "Roche Limit" is the critical distance where the two balance
Saturn’s moons are (mostly) outside of Roche Limit
Saturn’s rings are (mostly) inside the Roche limit.

Roche Limit (2.4 Saturn Radii)

Gaps in Saturn's Rings
Gaps in the rings are caused by resonances with the satellites
Example: Mimas causes the Cassini Division
Mimas makes one revolution in 23 hours. A ring particle in The Cassini Division makes one revolution in 11 ½ hours, or two revolutions in one Mimas period. This is resonance.

Analogy: There are “gaps” in asteroid belt caused by resonances with Jupiter
Even today, gravitational perturbations by Jupiter deplete certain orbits within the asteroid belt
The resulting gaps, called Kirkwood gaps, occur at simple fractions of Jupiter’s orbital period

Why is IO so active? Its so small it should have lost its heat long ago!
Red ring of sulfur ejected from Pele
Fresh deposits ejected from Pillan Patera partially cover the red ring from Pele

B.3: Moons & Minor Planets
Some of the moons are bigger than planet Mercury!

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Europa
Europa has no impact craters. It’s icy surface shows an intricate network of crossing cracks, similar to cracks in the Arctic ice pack on Earth.

There is very little vertical relief (no mountains or deep valleys).

Europa’s surface is very young.

Huygens Probe lands on Saturn’s Moon Titan!

• January 14, 2005. This moon is bigger than Mercury and has an atmosphere!
• Rounded boulders in foreground are about 4 - 15 cm across.
• The boulders are probably frozen H$_2$O.

Voyager at Uranus and Neptune

• Significant differences from Jupiter and Saturn
  – bluish color
  – Uranus very bland
  – Neptune faint belts and zones and also a few storms
  – much smaller (and less massive) than Jupiter and Saturn

Miranda (Uranus)

• huge fault canyons as deep as 20 kilometers
• Such a small moon should not have had any significant internal heating or evolution, so the features were quite a surprise.
• scientists believe that Miranda may have been shattered as many as five times during its evolution

Triton (moon of Neptune)

• Cold 38K, frozen methane and nitrogen
• Yet, evidence of volcanic activity!
• Where does the heat come from?