Chapter 8: The Outer Planets

Jupiter ♃

Mass: 318 $M_\oplus$

Density: 1330 kg/m^3

Distance from Sun: 5.20 A.U.

Rotation Rate: ~9^h 56^m

Oblateness: 0.065

Visual Appearance:
Through a telescope Jupiter appears as a slightly flattened disk crossed by alternating bands of light and dark material (clouds), and the Great Red Spot. Also, the four Galilean moons are visible.

Differential Rotation and Oblateness:
The fast rotation has two affects:

1. Oblateness: flattening of planet. Polar diameter smaller than the equatorial diameter. It is defined as (1 –polar diameter/equatorial diameter)

The measured oblateness is smaller than it would be if Jupiter was composed of just hydrogen and helium, which implies that it has a dense rocky core amounting to 10 to 15 $M_\oplus$.

2. Differential Rotation: Equatorial region rotates faster than the polar regions.
   Poles: 9h 55m 41s
   Equator: 9h 50m 28s

To measure the actual rotation period the period of rotation of the magnetic field is measured.
   Magnetic Field: 9h 55m 30s

Atmosphere

Composition	Hydrogen -	86.2%
	Helium -	13.6%
	Methane	Traces
	Ammonia	Traces
	Water Vapor	Traces

Concept Test

The atmosphere of Jupiter has few heavy elements due to

a) evaoration.
b) the lack of heavy elements in the outer solar system.
c) the vacuum-like power of the Great Red Spot.
d) gravitational settling towards the planet's center.

Coloration: Color due to complex chemical reactions involving sulfur and red phosphorus

Clouds: Three distinct layers consisting of ammonia ice, ammonium hydrosulfide ice, and water ice.

Belts and Zones: Due to the internal heat source of Jupiter.

Belts: lower in atmosphere, dark colored, cool air falling.

Zones: higher in atmosphere, light colored, warm air rising.

Zonal Flow: Underlying east and west wind flow. Wind speeds around 650 km/hr. Caused by the internal convection and fast rotation.

Weather Systems: (small scale)

Great Red Spot: Similar to a hurricane. Observed for over 300 years. Has counterclockwise circulation. High pressure system. Is higher than the surrounding clouds. Dimensions of around 12,000 by 25,000 km.

White ovals: Counterclockwise circulation. Color is an indication that their tops reside high in the atmosphere. Most are found in the southern hemisphere. High pressure regions.

Brown ovals: More common in the northern hemisphere. Holes in the atmosphere.

Internal Heat Source:
Radio measurements indicated that Jupiter puts out twice as much heat as it receives from the Sun. The source of the excess heat is heat left over from its formation.

Internal Structure:
Composition is basically the same as our Sun (hydrogen and helium).

Structure is based upon observations of the bulk properties of the planet(mass, radius, rotation, temperature, composition,...). A model of the interior is constructed that fits the observed properties.

Structure

Depth(km)	Temperature(K)	Pressure(atm)	State
0 - 20,000	300 - 11,000	10 - 3,000,000	molecular hydrogen
20,000 - 60,000	11,000 - 25,000	3,000,000 - 12,000,000	metallic hydrogen
60,000 - 71,400	25,000 - 40,000	12,000,000 - 50,000,000	rocky material

The rocky core is probably 15 times the mass of the Earth and was a key element in the formation of Jupiter's massive atmosphere.

Magnetosphere

1. Pressures within the interior are high enough to strip electrons from hydrogen atoms creating a sea of charged particles that form an electric current do to the rotation. This electric current generates a powerful magnetic field.

2. Magnetic field strength: 20,000 times the Earth's field strength.

3. Field extends out past the orbit of Saturn (4 A.U.).

4. Rotates once in $9^h\ 55^m\ 30^s$.

5. Consists mostly of electrons accelerated close to the speed of light.

6. Charged particles are confined to a flat current sheet lying on the magnetic equator.

7. Magnetic axis is inclined to the rotational axis by 10^o.

8. Radiation from fast moving electrons in a strong magnetic field is called synchrotron radiation.

Jupiter's Ring

1. Discovered by the Voyager spacecraft.
2. Three distinct regions: Halo, Gossamer, and Main rings.
3. Probably made of material chipped off the moons Metis and Adastrea.

Summary of the Galileo Probe

1. Atmosphere warmer and drier than expected. The three expected cloud regions were not found. May be due to the probe entering a hot spot in the atmosphere.

2. Stronger winds than expected. Wind speeds do not decrease with depth indicating that the source is the planet's internal heat.

3. Abundances of argon, krypton and xenon were higher than expected. Can be explained by taking into account the bombardment by planetismals after the planet's formation.

4. Lightning observed. Not as frequent as on the Earth (1/10) but more powerful discharges. Result is consistent with the observed absence of water clouds in the entry region.

Saturn ♄

Distance from Sun: 9.54 A.U.

Mass: 95 $M_{\oplus}$

Density: 687 kg/m^3

Eccentricity: 0.056

Rotation Rate: $10^h\ 14^m$

Oblateness: 0.11

Appearance through a small telescope: Rings, banding in the atmosphere and up to eight moons are visible.

Atmosphere:

1. Composition:

Molecular hydrogen	96.3%
Helium	3.25%
Methane	0.45%
Ammonia	0.05%

Smaller helium abundance due to helium sinking to the center of the planet.

2. Atmospheric structure is very similar to Jupiter except Saturn does not have the large spots or ovals. Overall color is much less than Jupiter. The difference in appearance is due to the fact that Saturn's gravity is weaker and thus the atmosphere is more extended and hazy.

3. Occasionally, large atmospheric disturbances are recorded as in the large white spot seen in 1994.

4. Atmospheric winds are stronger than on Jupiter (1800 km/hr vs. 650 km/hr).

Internal Structure:

1. Saturn's internal structure is very similar to Jupiter except Saturn has a much larger rocky core as indicated by its oblateness (0.11).

2. Saturn puts out more heat than it receives. The heat source is due to helium condensing out of its atmosphere since it is cooler.

Magnetosphere:

1. Same mechanism as in Jupiter.

2. Strength is about 1/20 that of Jupiter's field.

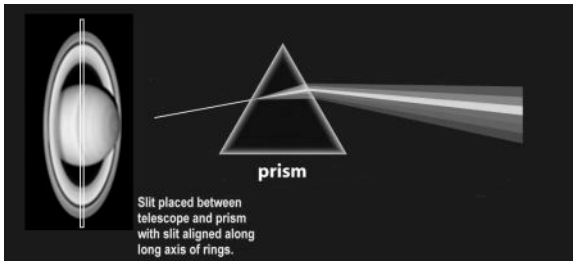
3. Not as many charged particles due to:
    a. lack of any major moons within the magnetic field.
    b. extensive ring system that sweeps up charged particles.

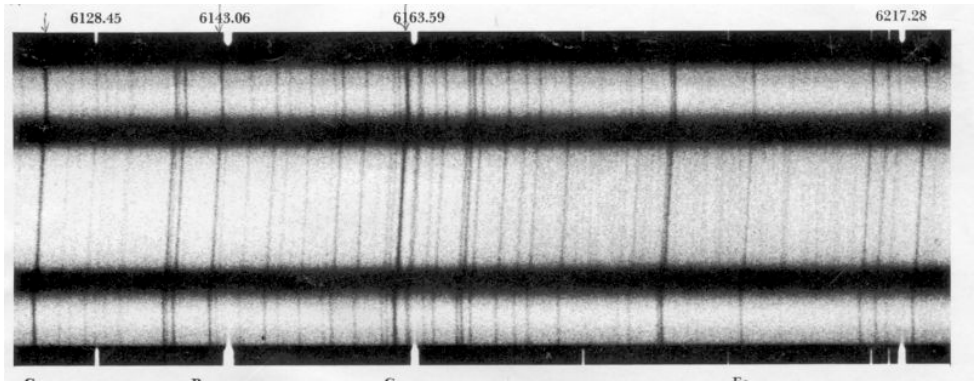
Ring System:

1. As seen from the Earth there are three distinct rings.
    a. A ring - moderately bright
    b. B ring - brightest
    c. C ring - very tenuous

The A and B rings are separated by the Cassini division.
A fainter division lies within the A ring called the Encke division.

2. Composition of rings was hypothesized by James Clerk Maxwell in 1857 to be composed of large numbers of small particles. his theory was confirmed in 1895 by James Keeler using spectroscopy by measuring the Doppler shift of reflected sunlight.





3. Ring particles are made of ices.

4. Origin of rings: Roche Limit - any moon caught inside will be broken up by the strong tidal forces of Saturn or any material within the Roche limit will be prevented from forming a moon.

5. Cassini division is due to a 2:1 orbital resonance with Mimas.

6. Encke division in the outer portion of the A ring is due to a small moon (Pan) orbiting within it.

Results from Voyager:

1. Rings are composed of tens of thousands of ringlets formed by spiral density waves.

2. Gaps are due to moonlets (10 - 20 km diameter) sweeping up material.

3. Cassini division not completely empty.

4. D, E, F,and G rings. E ring is outside the Roche limit and is probably due to volcanic eruptions on Enceladus.

5. Braided structure of the F ring explained by the interaction of the shepherd moons Prometheus and Pandora.

6. Radial spokes in the B ring formed by electromagnetic forces generated by static electricity generated by collisions between particles.

Results from Cassini:

1. Water ice is the primary component of the rings (99%).

2. The tiny moon Prometheus is perturbing the F-Ring, scalloping one edge bordering the Encke Gap.

3. The abundance of oxygen in the atmosphere rises and falls significantly over short time periods. Source of the atomic oxygen is thought to be from ice particles chipped off the rings and moons.

4. Winds speeds drop off dramatically above the cloud tops near the equator.

5. Two new tenuous rings.

6. The rings are probably only a few hundred million years old.

7. Major storm systems spark lightning.

8. Saturn's magnetic field is very dynamic. Rotation rate increased 6 minutes since the Voyager flyby.

Moons of Jupiter

The four largest moons are the Galilean moons (Io, Europa, Ganymede, and Callisto). In all there are 63 moons (18 were discovered in Feb. 2003 alone).

Galilean Moons: All four are in synchronous rotation due to tidal forces.

1. Io

    a. Diameter: 3630 km (1.21 D_{moon}).
    b. Rocky composition. Density = 3550 kg/m^3.
    c. Active volcanoes due to tidal flexing by Jupiter
    d. Molten silicate interior.
    e. Sulfur and frozen sulfur dioxide crust.
    f. Youngest surface of any solar system body. The surface is no older than a dozen years.
    g. Thin (temporary) atmosphere of sulfur dioxide.
    h. Io's volcanoes spew heavy ions into Jupiter's magnetic field producing the Io plasma torus.
    i. Io's orbit is not perfectly synchronous (orbit is not a perfect circle) due to tidal effects from Europa.

2. Europa
    a. Diameter: 3138 km (0.66 D_{moon}).
    b. Relatively few craters, many cracks tens of km wide. Tectonic activity?
    c. Surface is composed of water ice. Liquid water underneath evidence of this comes from the Galileo space probe which has revealed indications of ice flows on its surface.
    d. Rocky interior. Density = 3040 kg/m^3.

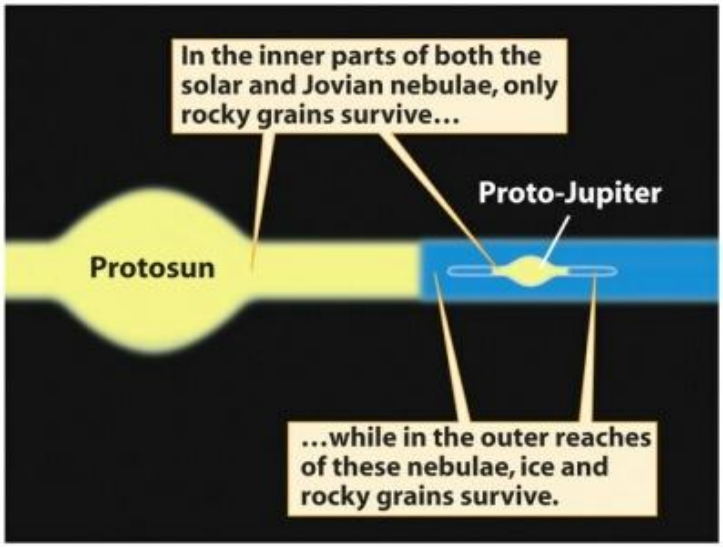
3. Ganymede

    a. Diameter: 5262 km (2.03 D_{moon}). Density = 1940 kg/m^3.
    b. Larger than Mercury and Pluto.
    c. Composition is ice and rock.
    d. Heavily cratered. Has maria made of frozen water.
    e. Had early plate tectonics (3 billion years ago) when its ice crust was thinner, which is apparent from the groves and ridges.
    f. Has a magnetic field, which is induced by Jupiter's magnetic field. Discovered by the Galileo spacecraft.

4. Callisto

a. Diameter: 4800 km. Density = 1810 kg/m^3.
b. Very heavily cratered with fewer groves.
c. Most prominent feature is a series of concentric ridges formed by an impact.
d. Composition is ice and rock.

We can compare Jupiter and its Galilean moons to the solar system in that they are like a miniature solar system with the denser bodies closer to Jupiter and the icy moons farther from planet.



Moons of Saturn:

In all there are 37 moons. (6 discovered by Cassini spacecraft)

1. Titan

a. Diameter: 5150 km. Density = 1900 kg/m^3.
b. Dense atmosphere (1.6 atm.). Composed of nitrogen, argon, and methane with traces of hydrogen, ethane, propane, carbon monoxide, and others. Titan has liquid methane on its surface.
c. Rocky core surrounded by a mantle of ice.

2. Rhea

a. Diameter: 1530 km. Density = 1300 kg/m^3.
b. Has wispy terrain due to some kind of release of water.

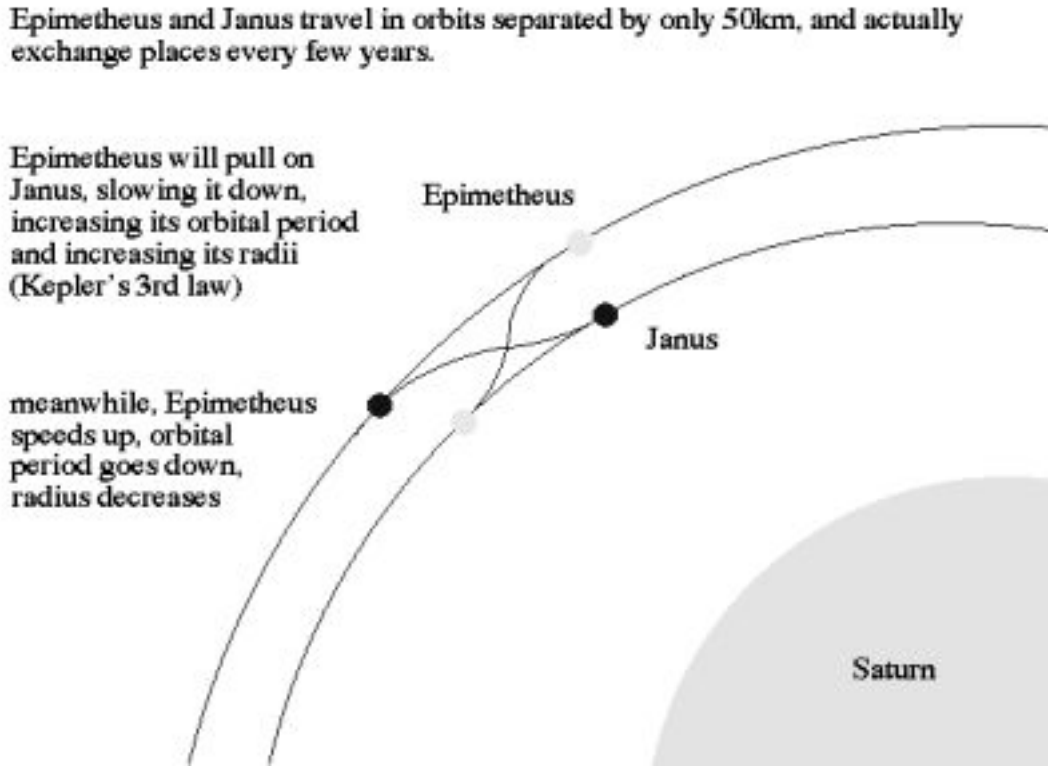
3. Tethys and Dione

a. Diameters of 1050 and 1120 km
b. Tethys shows wispy terrain.
c. Dione has "maria".

4. Mimas
    a. Diameter: 394 km
    b. Responsible for the Cassini division due to its close proximity to the rings (orbital resonances).
    c. Prominent feature is the crater Herschel.

5. Enceladus
    a. Diameter: 502 km
    b. May have water volcanism which produces the E ring.

6. Co-orbital satellites: Janus and Epimetheus
    a. "Share" an orbit. Their orbits are only 50 km apart.
    When the moon in the smaller orbit catches up with the other moon their mutual gravitation causes them to exchange orbits.



7. Iapetus ("eye AP i tus")
    a. Diameter: 1440 km
    b. Its leading hemisphere is dark, which remains unexplained.

Almost all of the moons are more heavily cratered on the side facing into their orbital motion.

Cassini-Huygens Results

Titan:

1. Landed on the equivalent of mud. Surface is wet with liquid methane.

2. Drainage channels and what looked like a lake shore were seen during the descent.

3. Surface temperature of -291 F.

4. Eroded looking "rocks" seen strewn around the landing site. Rocks are probably water ice.

5. 350 images received.

6. Some data was lost due to a programming bug. 350 images were lost. Wind speed experiment also lost, but Earth based radio telescopes managed to pick up the wind speed data.

Other Moons:

1. Six new tiny moons (diameters of just a few km).
   Methone, and Pallene - located between orbits of Mimas and Enceladus.
   Polydeuces - follows Dione by 60 degrees in a Langrange point of Dione.
   S/2004 S3
   S/2004 S4
   S/2004 S6

2. A number of Saturn's moons appear to be more like rubble piles.

3. Mountains on Iapetus appear to be 10 to 20 km tall.

4. Dione shows ice cliffs formed by tectonic forces.

Uranus ♅

Distance from Sun: 19.2 A.U .

Mass: 14.6 $M_{\oplus}$

Density: 1318 kg/m^3

Rotation Rate: 17.2 hrs.

Oblateness: 0.03

Axial Tilt: 98 degrees

A. Discovered in 1781 by Sir William Herschel using a six inch telescope.

B. Consequence of axial tilt:

a. Extreme seasons (depending where an observer is located).
days and nights can be as long as 42 years.

Concept Test
Seasons on Uranus are a) one fourth of Uranus' year, or about 20 Earth years long. b) as long as Uranus' year. c) non-existent. d) four times Uranus' year, or about 320 Earth years.

D. Differential Rotation:

a. Rotates faster at the poles than at the equator!

E. Atmosphere:

a. Composition

hydrogen	82.5%
helium	15.2%
methane	2.3%
ammonia	insignificant

b. Weather

1. Cloud patterns are very faint.
2. Wind speeds ~700 km/hr.

3. Very uneven solar heating.

F. Magnetosphere

a. 100 times stronger than Earth's field.
b. magnetic axis tilted 60 degrees to the rotational axis
c. magnetic axis is offset from the center of the planet.

G. Interior

a. Not well understood.
b. Rocky core surrounded by mantle of Ionic slush (dissolved ammonia) which is in turn surrounded by a liquid molecular hydrogen and helium shell
c. Ionic slush generates the magnetic field.

H. Moons

a. 27 moons (21 named and 6 unnamed) prior to 2004. Two additional moons discovered using the Hubble Space Telescpe in 2004 to bring the total to 29.
b. Largest is Titania (1610 km), followed by Oberon (1550 km).
c. 5 largest moons are visible from the Earth.
d. Icy compositions (densities: 1300 to 1600 kg/m^3).
e. Very dark compared to Saturn's moons. May be due to radiation effects that have created dark organic matter from the methane ice that is more common in the outer solar system.

I. Rings

a. Discovered in 1977 during a stellar occultation (11 rings).
b. Dark.
c. Narrow with wide gaps. All of the rings have shepherd moons.
d. Only a few tens of meters thick.
e. Two new rings discovered, using the Hubble Space Telescope, in 2004.

Neptune ♆

Distance from Sun: 30.1 A.U.

Mass: 17.2 $M_\oplus$

Density: 1638 kg/m^3

Rotation Rate: 17.3 hrs. (clouds), 16.1 hrs (interior)

Oblateness: 0.026

Independently predicted in the 1840s by Adams and Leverrier using perturbation theory. Located in 1845.

A. Atmosphere

a. Composition: similar to Uranus

Hydrogen	79%
Helium	18%
Methane	3%

b. Weather:

1. Winds blow east to west at speeds over 2000 km/hr!
2. Great Dark Spot: like Jupiter's Great Red Spot. Has since vanished (Hubble Telescope observation.)

c. Equatorial rotation rate : ~18 hrs.
Polar rotation rate: ~12 hrs.

B. Magnetosphere

a. 100 times stronger than the Earth's magnetic field.
b. Magnetic axis tilted 46 degrees to rotational axis.
c. Magnetic axis is off centered.

C. Interior

a. Same basic structure as Uranus.
b. Rotates in 16.1 hrs.
c. Radiates 2.6 times more heat than it receives. Source same as Jupiter (gravitational contraction).

D. Moons

a. 13 moons. Five of them were discovered in the last two years.
b. Largest is Triton (2760 km). Has a retrograde orbit. Has nitrogen geysers. Shows evidence of ice volcanoes.
c. Nereid (other moon visible from Earth) has a very eccentric orbit(eccentricity = 0.75).

E. Rings

a. Discovered by Voyager 2 in 1989.
b. Four rings. Each is clumpy, which may be due to shepherd satellites.

Pluto ♇

Distance from Sun: 39.5 A.U.

Mass: 0.0025 $M_{\oplus}$

Diameter: 2380 km (1/5 Earth's diameter)

Density: 1750 kg/m^3

Eccentricity: 0.25

Sidereal Period: 248.6 years. Locked into a 3:2 orbital resonance with Neptune.

Axial Tilt: 120 degrees

Discovered in 1930 by Clyde Tombaugh.

Composition: Similar to icy Jovian moons (water ice and methane ice). The surface is covered by frozen carbon monoxide (CO), methane (CH_4), and nitrogen (N_2), which requires a surface temperature of 35 K.

Albedo: 0.60

Atmosphere:
Surface pressure of 10 m bar (1/100,000 Earth's surface pressure).
Composed of methane (CH_4), carbon monixide (CO), and nitrogen (N_2). This atmosphere is thought to be due to an active interior.

Over the billions of years the atmosphere should have eroded any surface features through sublimation.

Moon: Charon

Diameter: 1190 km

Period: 6.4 days

Distance from Pluto: 19,700 km

Orbit:
Plane of the orbit is nearly perpendicular to Pluto's motion around the Sun, which results in Charon alternately passing in front of and behind Pluto when the Earth is in the same plane as Charon's orbit. This has allowed astronomers to determine the sizes of Pluto and Charon.

Albedo: 0.40

Composition: Surface is covered by water ice. Thought to be a result of Pluto's atmosphere depositing on Charon. Water ice coating has probably preserved Charon's original surface features.

Atmosphere: Very recent measurements (July 10, 2005) of a stellar occultation indicate a possible atmosphere (1/10 of Pluto's).

Two new moons discovered in May 2005 using the Hubble Space Telescope. Provisionally designated S/2005 P1 and S/2005 P2.