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http://moodle.gla.ac.uk/physics/moodle/

Astronomy A1X 2006-07
Solar System Physics I - Lecture Plan

Introductory Tour of the Solar System — 1 lecture

- Qualitative description of the Sun, planets, moons and minor bodies, contrasting Jovian and terrestrial planets
- Vital statistics
- Overview of Solar System formation

Gravitation and Solar System physics — 1.5 lectures

- Newton's law of gravitation and link to A1X Dynamical Astronomy
- Surface gravity and escape velocity
- Tidal forces

Solar System Physics 1 – Lecture Plan

The physics of planetary atmospheres — 1.5 lectures

- The ideal gas law and velocity of gases
- Hydrostatic equilibrium and atmospheric scale heights

The Jovian planets and their moons — 2 lectures

- Internal and atmospheric structure and composition
- Ring systems and Roche stability
- Physical properties of the main satellites
- *Case studies: Titan and the Galilean moons*

Lecture 1: A Tour of the Solar System

Some vital statistics:-

The Solar System consists of:-

- the Sun,
- its **8** planets,
- their moons,
- dwarf planets, asteroids and comets,
- the 'Solar wind'

- Astronomers have studied the motions of the Sun, Moon and planets for thousands of years (see A1X Positional Astronomy).

The Sun: some vital statistics:-

The Sun is a star: a ball of (mainly) hydrogen gas, 700,000 km in radius (about 100 Earth radii)

It generates heat and light through **nuclear fusion**:

Surface temperature = 5800K

Central temperature = 15 million K

Balance (hydrostatic equilibrium) maintained between *pressure* and *gravity*

The Sun's outer atmosphere, or *corona*, is very hot (several million K) – heated by twisting of the Sun's magnetic field?...

Mean Earth – Sun distance = **Astronomical Unit**

149,597,870 km

1 A.U. = 107 solar diameters

The orbits of the planets are ellipses (see *A1X* Dynamical *Astronomy*) and lie in, or close to, a plane – the ecliptic.

The planets divide into two groups:-

Inner *Terrestrial* planets: small, rocky — Mercury, Venus, Earth, Mars

Outer *Jovian* planets: gas giants — Jupiter, Saturn, Uranus, Neptune

Pluto is a 'misfit' – Kuiper Belt object (planetesimal); together with asteroids and comets, 'debris' from formation of the Solar System.

Lectures 4-6: Key Features of the Jovian and Terrestrial Planets

The Jovian planets are: **Jupiter, Saturn, Uranus and Neptune**

The terrestrial planets are : **Mercury, Venus, Earth and Mars**

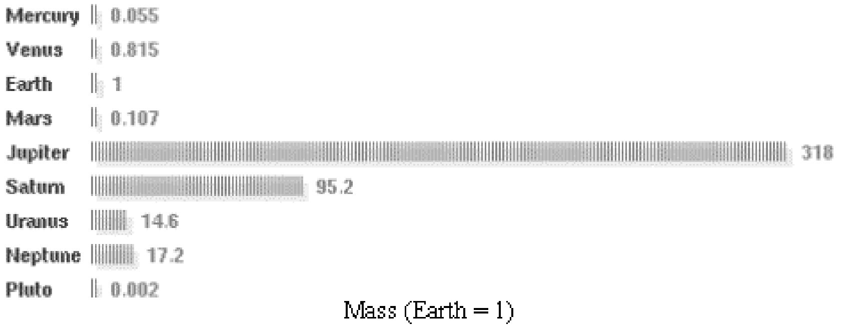
See Chapter 6, Table 6.2 Astronomy Today

We can summarise the differences between them as follows:-

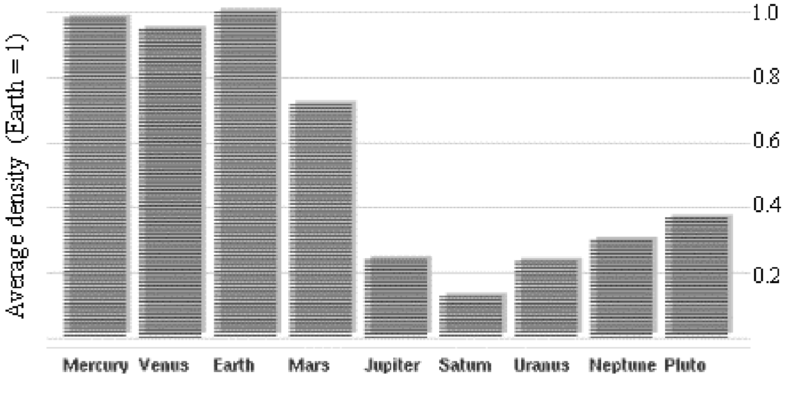
See SSP2 Lectures

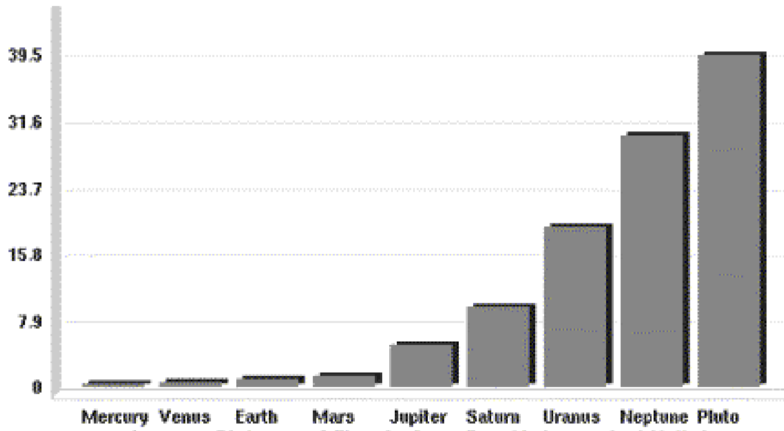
Terrestrial Planets	**Jovian Planets**
Lower mass, smaller radii	Higher mass, larger radii
Near the Sun	Distant from the Sun
[Higher surface temperature	Lower surface temperature]
Higher average density	Lower average density
H and He depleted	Abundant H and He
Solid surface	Gaseous / Liquid *
Slower rotation period	Rapid rotation period
No rings	Many rings
Few satellites	Many satellites

* Rocky core deep inside

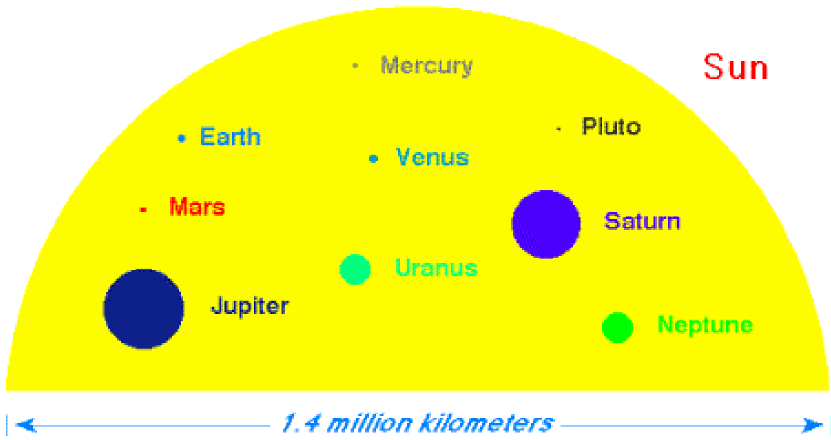


Mass (Earth = 1)





Average distance from the Sun (AU)



Abundance of H and He

We can use the **ideal gas** argument of Lecture 3 to estimate the temperature required for hydrogen and helium to escape from a planetary atmosphere:-

$$T_{esc} = \frac{1}{54}\frac{GM_P m}{kR_P} = \frac{1}{54}\frac{GM_P \mu m_H}{kR_P}$$

$$= \frac{6.673\times10^{-11}\times5.976\times10^{24}\times1.674\times10^{-27}\left(M_P/M_{\mathrm{Earth}}\right)\mu}{54\times1.381\times10^{-23}\times6.378\times10^{6}\left(R_P/R_{\mathrm{Earth}}\right)}\ \mathrm{K}$$

$$= \frac{140\left(M_P/M_{\mathrm{Earth}}\right)\mu}{\left(R_P/R_{\mathrm{Earth}}\right)}\ \mathrm{K}$$

Abundance of H and He

For molecularHydrogen, $\mu = 2$ so the escape temperature for the **Earth** is **280 K**

This explains why the Earth has not retained its atmospheric molecular hydrogen.

(In fact, when the solar system was forming, the inner Solar System was too hot to retain lighter elements, such as H and He; these are absent from all terrestrial planet atmospheres. See SSP2 lectures on formation of the solar system.)

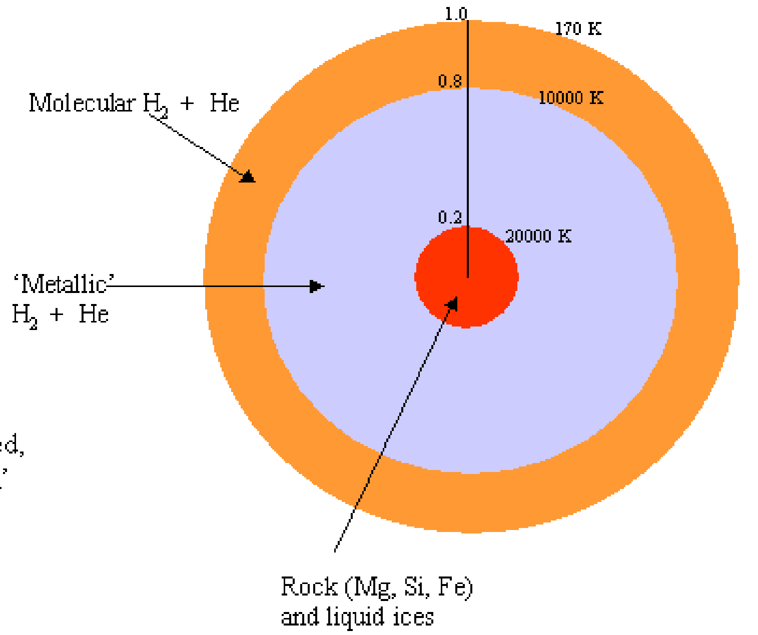
For, e.g. molecular Nitrogen, $\mu = 28$ so the escape temperature for the Earth is **3920 K**

So the Earth's atmosphere *can* retain its molecular nitrogen.

Plugging in the numbers for the Jovian planets, for molecular **Hydrogen**; these escape temperatures are so high that the planets will *not* have lost their atmospheric hydrogen.

Planet	**Radius (Earth=1)**	**Mass (Earth=1)**	T_{esc}
Jupiter	11.209	317.8	7939 K
Saturn	9.449	95.16	2820 K
Uranus	4.007	14.53	1015 K
Neptune	3.883	17.15	1237 K

Internal structure of Jupiter



Upper atmosphere:

90% H_2
10% He
0.2% CH_4 , ammonia, water

Lower atmosphere:

High pressure, density 'squeezes' H_2

Molecular bonds broken; electrons shared, as in a metal – 'liquid metallic hydrogen'

Core:

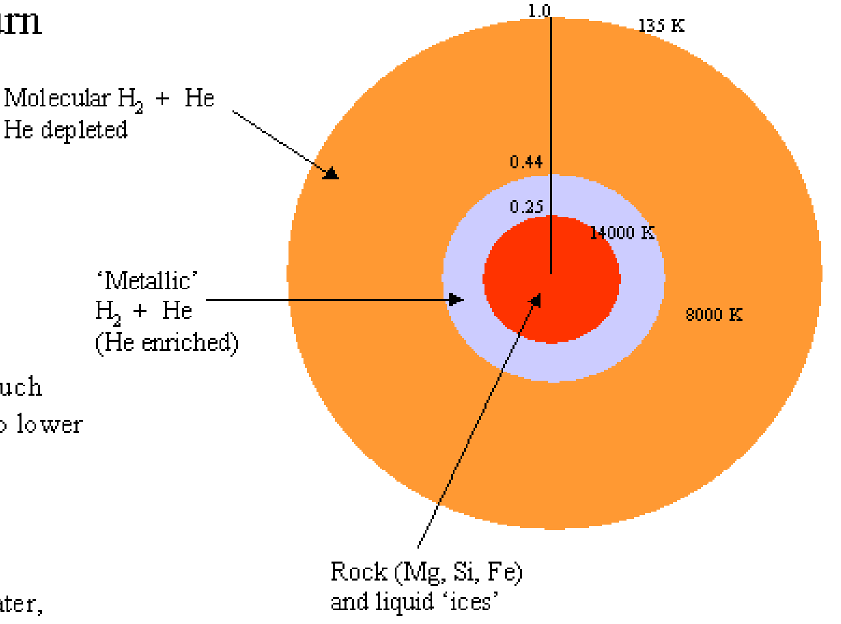
Dense, 'soup' of rock and liquid 'ices' (water, methane ammonia) of about 15 Earth masses

Evidence of internal heating – gravitational P.E. released during planetary formation (collapse of gas cloud)

[see SSP2 and A1Y Stellar Astrophysics]

Metallic hydrogen gives Jupiter a strong magnetic field (19000 times that of the Earth)

Internal structure of Saturn



Upper atmosphere:

97% H_2
3% He
0.2% CH_4 , ammonia, water

Lower atmosphere:

'liquid metallic hydrogen' (but at much greater depth than in Jupiter – due to lower mass and density)

Core:

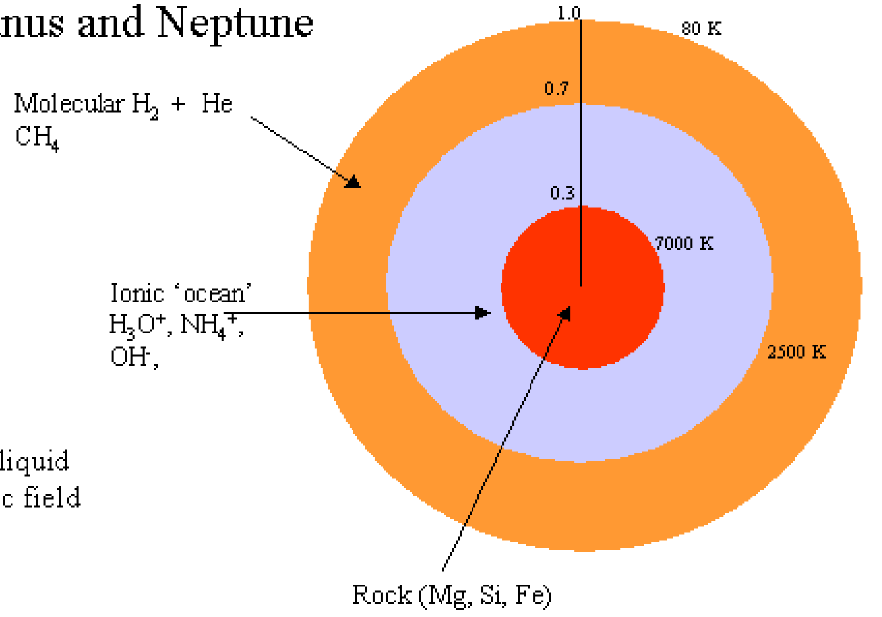
Dense, 'soup' of rock and 'ices' (water, methane ammonia) of about 13 Earth masses

Internal heating not entirely explained by planetary formation; extra heating from release of P.E. as heavier He sinks.

Effect more pronounced for Saturn, as outer atmosphere cooler to begin with

Metallic hydrogen gives Saturn a strong magnetic field (but weaker than Jupiter's)

Internal structure of Uranus and Neptune



Upper atmosphere:

Uranus	Neptune
83% H_2	74% H_2
15% He	25% He
2% CH_4	1% CH_4

Lower atmosphere:

Pressures not high enough to form liquid metallic hydrogen; weaker magnetic field due to ionic 'ocean'

Core:

Dense, 'soup' of rock, also about 13 Earth masses

Internal heating also important – particularly for Neptune (similar surface temperature to Uranus, despite being 1.5 times further from the Sun)

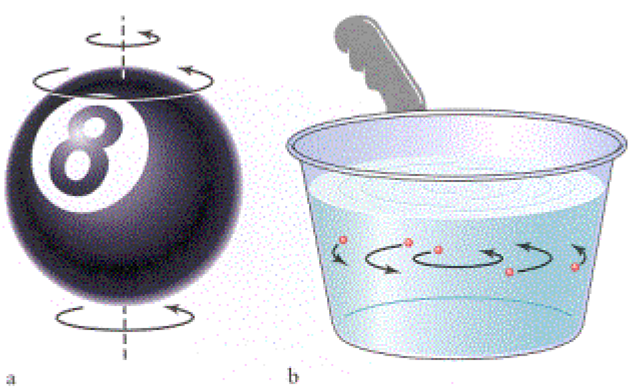
Cores of Uranus and Neptune form much higher (70% to 90%) fraction of total mass, compared with Jupiter (5%) and Saturn (14%)

Rotation of the Jovian Planets

Jupiter, Saturn, Uranus and Neptune rotate very rapidly, given their large radii, compared with the terrestrial planets.

Also, the Jovian planets rotate ***differentially*** – not like a solid body (e.g. a billiard ball) but as a fluid (e.g. grains of rice in a pot of water).

We see this very clearly on Jupiter, where the Distinct cloud bands and belts rotate at different speeds

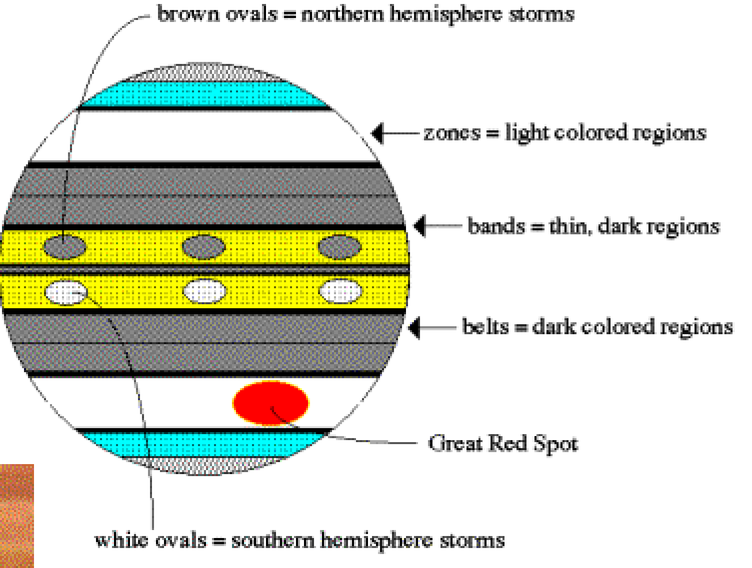


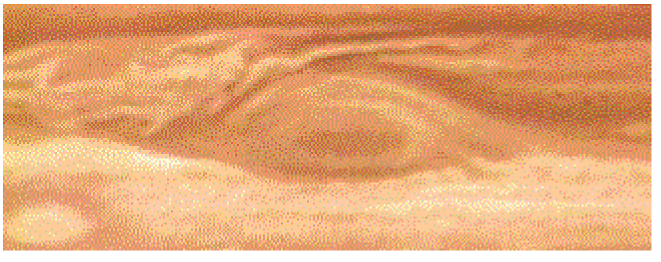
Planet	Rotation Period *
Mercury	58.6 days
Venus	243 days
Earth	24 hours
Mars	24 h 37 m
Jupiter *	9 h 50 m
Saturn *	10 h 14 m
Uranus	17 h 14 m
Neptune	16 h 7 m
Pluto	6.4 days

* At Equator

On Jupiter we also see clearly that the cloud belts contain oval structures.
These are storms; the most famous being the Great Red Spot.
This is a hurricane which has been raging for hundreds of years. It measures about 40000km by 14000km

Winds to the north and south of the Great Red Spot blow in opposite Directions; winds within the Spot blow counterclockwise, completing One revolution in about 6 days.



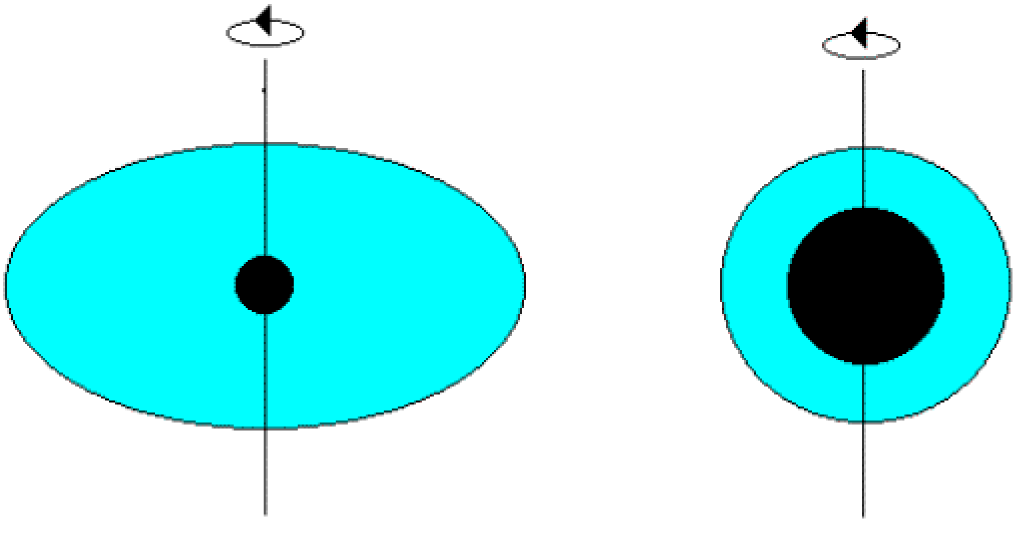


The Jovian planets are significantly flattened, or **oblate.**

The effect is most pronounced for Jupiter and Saturn, which have relatively smaller cores

e.g. for Jupiter, polar diameter = 133708km (6.5% less that equatorial diameter)

high rotation rate + fluid planetary structure = oblateness



the smaller the core of a Jovian world, the more oblate its shape

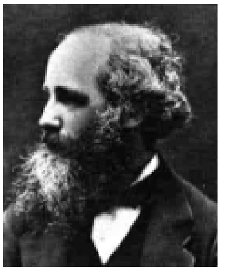
Ring Systems of the Jovian Planets: Saturn's Rings

All four Jovian planets have **RING SYSTEMS**.

The Saturn ring system is the most impressive: it is easily visible from Earth with a small telescope, and superficially appears like a solid structure.

In fact the rings consist of countless numbers of lumps of ice and rock, ranging in size from ~1cm to 5m in diameter, all independently orbiting Saturn in an incredibly thin plane - believed to be less than 1 kilometre in thickness.

(Compare this with the diameter of the outermost ring - 274000 km. If Saturn's rings were the thickness of a CD, they would still be more than 200m in diameter!)



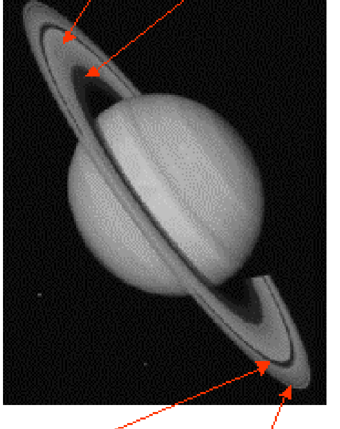
In 1857 James Clerk Maxwell proved that Saturn's rings couldn't be solid; if they *were* then **tidal forces** would tear them apart. He concluded that the rings were made of 'an indefinite number of unconnected particles'

(see later for more on tidal forces)

Saturn's rings are quite bright; they reflect about 80% of the sunlight that falls on them. Astronomers long suspected that they were made of ice and ice-coated rock, and this was confirmed in the 1970s when **absorption lines** of water were observed in the **spectrum** of light from the rings.

(See A1Y Stellar astrophysics for more on spectra and absorption lines)

Ground-based observations show only the **A**, **B** and **C** rings.

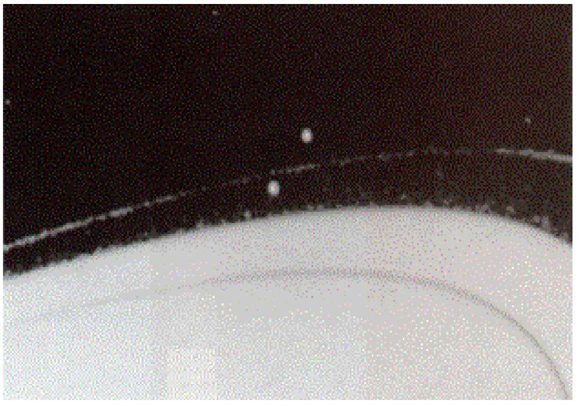


In the 1980s the **Voyager** spacecraft flew past Saturn, and showed that there are thousands of **'ringlets'** - even in the **Cassini Division** (previously believed to be a gap in the ring system).

Voyager also discovered a D ring, (inside the C ring), and very tenuous E, F and G rings outside the A ring, reaching out to about 5 planetary radii.

The F ring shows 'braided' structure, is very narrow, and contains large numbers of ~1μm particles

The structure of the F ring is believed to be controlled by the two 'shepherd moons' - Pandora and Prometheus - which orbit just inside and outside it. The gravitational influence of these moons confine the F ring to a band about 100km wide



Ring Systems of the other Jovian Planets

- Jupiter's ring system is much more tenuous than Saturn's. It was only detected by the Voyager space probes.

  The ring material is believed to be primarily dust, and extends from near Jupiter to about 3 planetary radii.

- Uranus' rings were discovered in 1977, during the **occultation** of a star, and were photographed by Voyager 2 in 1986.

  There are 11 rings in total, ranging in width from 10km to 100km. The ring particles are very dark (reflecting only 1% of sunlight) and about 1m across. Some rings are 'braided', and the thickest ring has shepherd moons. There is also a very thin layer of dust between the rings - probably the result of collisions.

- Neptune's rings were also first discovered from occultation observations, and were photographed by Voyager 2 in 1989. There are 4 rings: two narrow and two diffuse sheets of dust. One of the rings has 4 'arcs' of concentrated material.

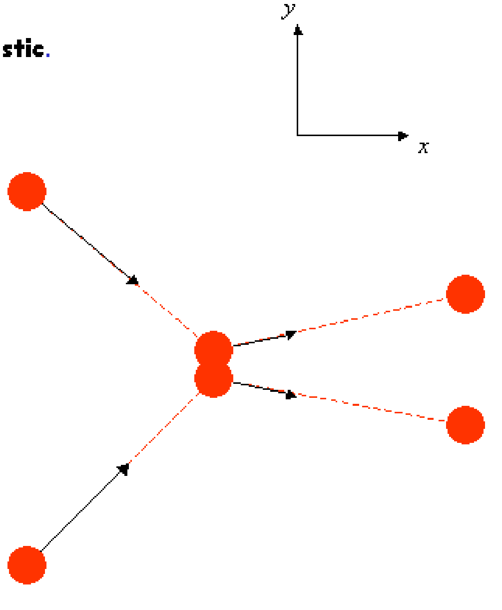
Why are the ring systems so thin?

Collisions of ring particles are **partially inelastic.**

Consider two particles orbiting e.g. Saturn in orbits which are slightly tilted with respect to each other.

Collision reduces difference of y components, but has little effect on x components

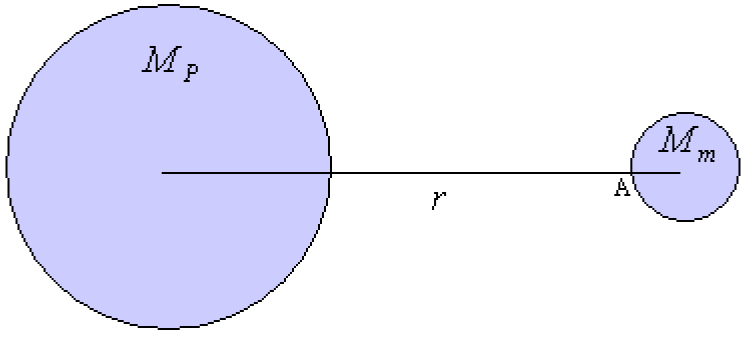
$\Longrightarrow$ thins disk of ring particles



How do ring systems form?

The ring systems of the Jovian planets are the result of **tidal forces**. During planetary formation, tidal forces prevented any material (planetesimals) that was too close to the planet clumping together to form moons. Also, any moons formed further out which later strayed too close to the planet would be tidally disrupted.

We can estimate the orbital radius at which a moon will break apart, due to tidal forces. Consider a moon, of mass M_m and radius R_m, in a circular orbit of radius r from a planet of mass M_P and radius R_P



Assume for simplicity, spherical planet and moon

Force on a unit mass at A due to gravity of **moon alone** is

$$F = \frac{G M_m}{R_m^{\ 2}}$$

Tidal force at A due to gravity of **planet** is *

$$F_T = \frac{2 G M_P R_m}{r^3}$$

* Putting $dr = R_m$

We assume, as an order-of-magnitude estimate that the moon is tidally disrupted if

$$F_T > F_G$$

i.e.

$$\frac{2 G M_P R_m}{r^3} > \frac{G M_m}{R_m^{\ 2}}$$

Substituting $M_P = \frac{4\pi}{3} \bar{\rho}_P R_P^{\ 3}$ and $M_m = \frac{4\pi}{3} \bar{\rho}_m R_m^{\ 3}$

$\Longrightarrow$ Moon is tidally disrupted if

$$r < 2^{1/3} \left(\frac{\bar{\rho}_P}{\bar{\rho}_m} \right)^{1/3} R_P$$

More careful stability analysis

$$r < 2.456 \left(\frac{\bar{\rho}_P}{\bar{\rho}_m} \right)^{1/3} R_P \quad = \quad \text{Roche Limit}$$

How do ring systems form?

e.g. for **Saturn**, from the Table of planetary data:- $\bar{\rho}_P \approx 700\,\mathrm{kg\,m^{-3}}$

Take a mean density typical of the other moons:- $\bar{\rho}_m \approx 1200\,\mathrm{kg\,m^{-3}}$

This implies

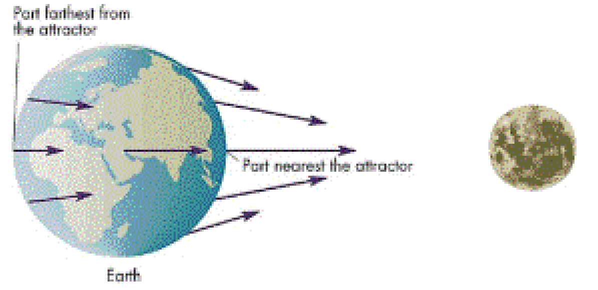
$$r_{RL} = 2.456 \times \left(\frac{700}{1200}\right)^{1/3} \times R_p = 2.05\,R_p$$

Most of Saturn's ring system ***does*** lie within this Roche stability limit, and ***all*** of its moons lie further out!

More on Tidal Forces

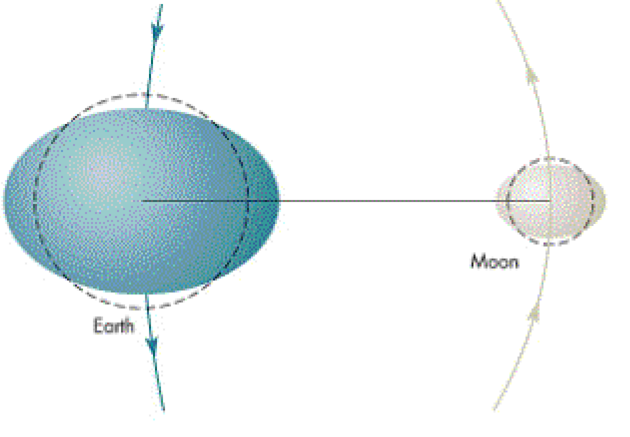
Of course, tidal forces also have an effect (albeit less destructive) *outside* the Roche stability limit.

Consider the effect of the Moon's tide on the Earth (and vice versa).



The tidal force produces an oval bulge in the shape of the Earth (and the Moon)

There are, therefore, **two** high and low tides every ~25 hours.



(Note: not every 24 hours, as the Moon has moved a little way along its orbit by the time the Earth has completed one rotation. Thus high and low tides are not at the same time each day)

More on Tidal Forces

The Sun also exerts a tide on the Earth.

Now, $F_T \propto \frac{M_P}{r^3}$ so $\frac{F_{T,\mathrm{Sun}}}{F_{T,\mathrm{Moon}}} = \frac{M_{\mathrm{Sun}}}{M_{\mathrm{Moon}}}\left(\frac{r_{\mathrm{Moon}}}{r_{\mathrm{Sun}}}\right)^3$

$M_{\mathrm{Sun}} = 1.989\times10^{30}\ \mathrm{kg}$ $\quad M_{\mathrm{Moon}} = 7.35\times10^{22}\ \mathrm{kg}$

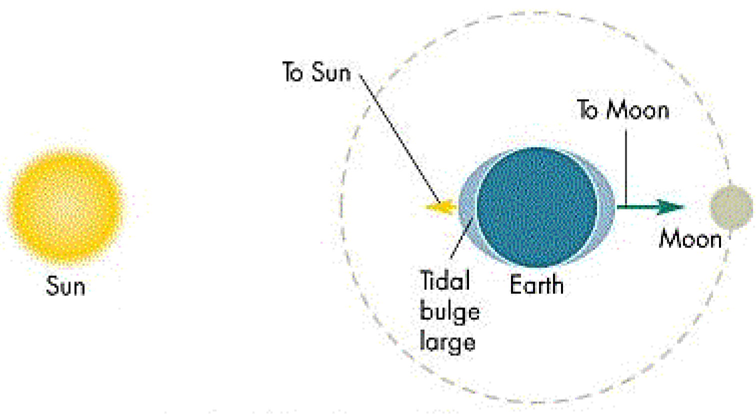
$r_{\mathrm{Sun}} = 1.496\times10^{11}\ \mathrm{m}$ $\quad r_{\mathrm{Moon}} = 3.844\times10^{8}\ \mathrm{m}$

Hence

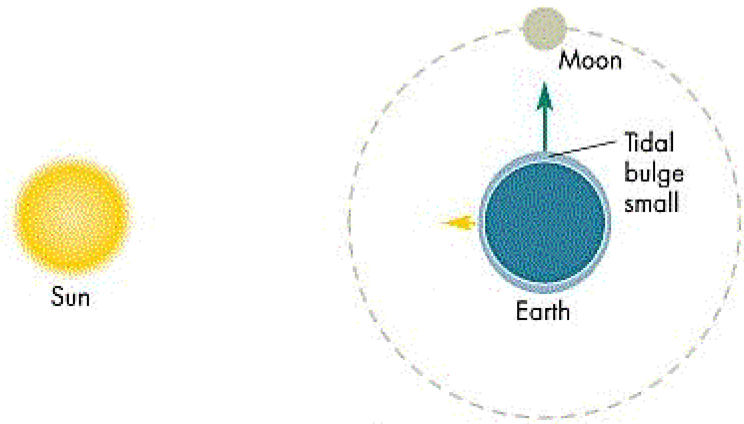
$$\frac{F_{T,\mathrm{Sun}}}{F_{T,\mathrm{Moon}}} = \frac{M_{\mathrm{Sun}}}{M_{\mathrm{Moon}}}\left(\frac{r_{\mathrm{Moon}}}{r_{\mathrm{Sun}}}\right)^3 \approx 0.5$$

i.e. the tidal forces on the Earth due to the Sun and Moon are **comparable**.

Spring tides occur when the Sun, Moon and Earth are aligned (at Full Moon and New Moon). High tides are significantly higher at these times.



Neap tides occur when the Sun, Moon and Earth are at right angles (at First Quarter and Third Quarter). Low tides are significantly lower at these times.



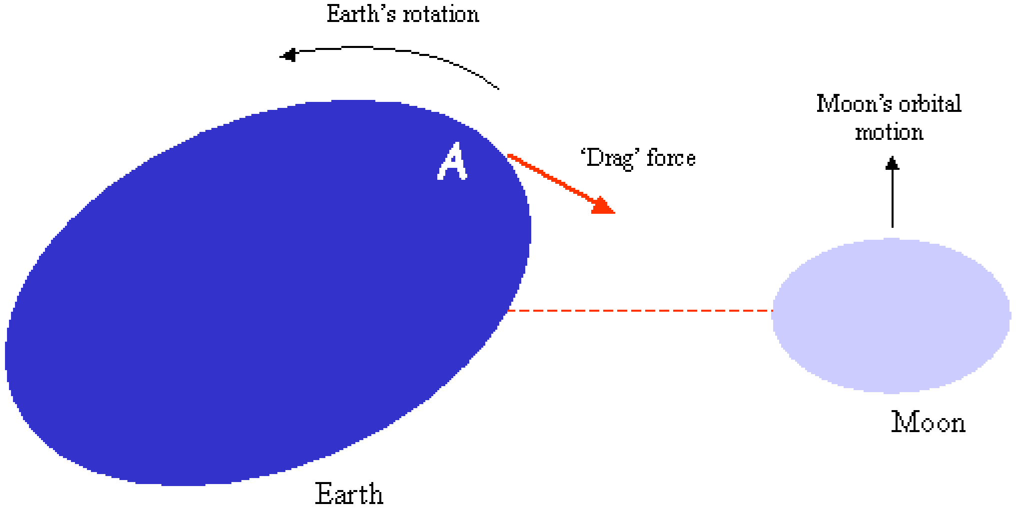
Lecture 6

Even if there were no tidal force on the Earth from the Sun, the Earth's tidal bulge would **not** lie along the Earth-Moon axis. This is because of the Earth's rotation.

The Earth's rotation carries the tidal bulge ahead of the Earth-Moon axis. (The Earth's crust and oceans cannot instantaneously redstribute themselves along the Earth-Moon axis due to friction)

The *Moon* exerts a drag force on the tidal bulge at *A*, which slows down the Earth's rotation.

The length of the Earth's day is increasing by 0.0016 sec per century.



At the same time, bulge *A* is pulling the *Moon* forward, speeding it up and causing the *Moon* to spiral outwards. **This follows from the conservation of angular momentum.**

The *Moon*'s semi-major axis is increasing by about 3cm per year.

- Given sufficient time, the Earth's rotation period would slow down until it equals the Moon's orbital period – so that the same face of the Earth would face the Moon at all times. We call this synchronous rotation

  (This will happen when the Earth's "day" is 47 days long)

  In the case of the Moon, synchronous rotation has *already happened !!!*

- Tidal locking has occurred much more rapidly for the Moon than for the Earth because the Moon is much smaller, and the Earth produces larger tidal deformations on the Moon than vice versa.

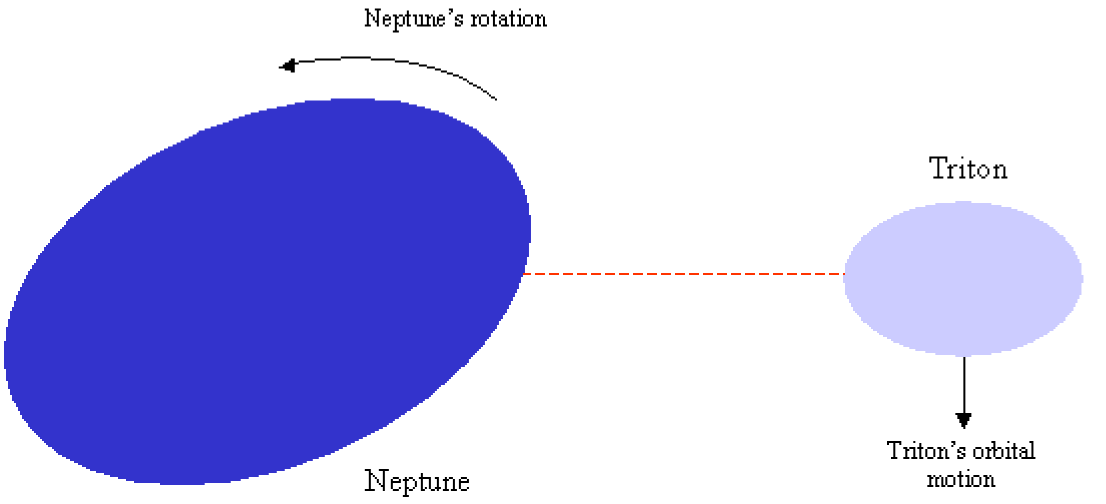
- The Moon is not exactly 'tidally locked': over about 30 years, 59% of its surface is visible from the Earth. This is because of a wobble known as *Libration* – which is caused by the gravitational perturbations of the Sun (and other planets) on the Earth-Moon system, and the fact that the Moon's orbit is slightly eccentric.

- Many of the satellites in Solar System are in synchronous rotation, e.g.:-

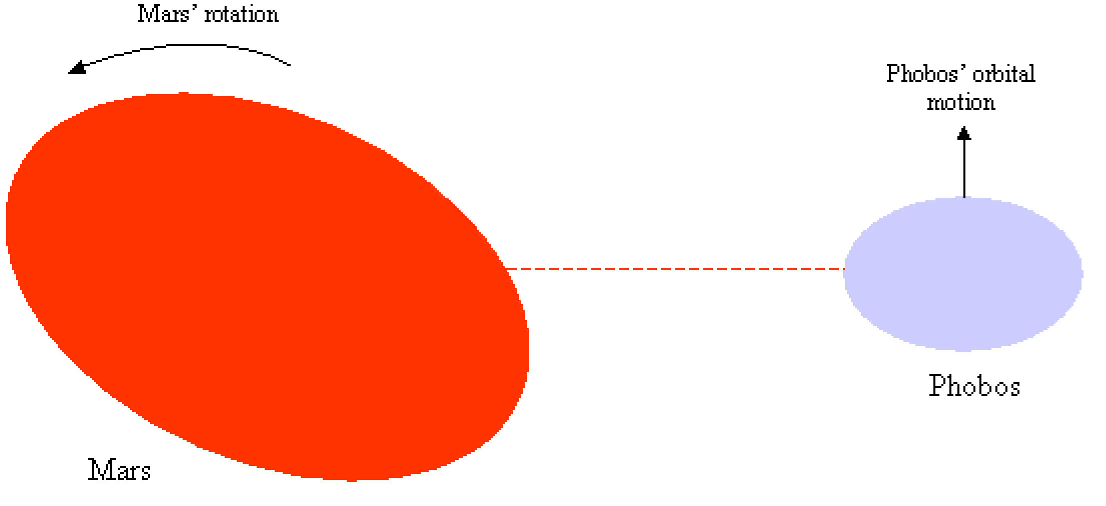
Mars:	Phobos and Deimos
Jupiter:	Galilean moons + Amalthea
Saturn:	All major moons, except Phoebe + Hyperion
Neptune:	Triton
Pluto:	Charon

- Pluto and Charon are in mutual synchronous rotation: i.e. the same face of Charon is always turned towards the same face of Pluto

- Triton is in synchronous rotation, but is orbiting Neptune on a *retrograde* orbit (i.e. in the opposite direction to Neptune's rotation).



In this case Neptune's tidal bulge acts to ***slow down*** Triton. The moon is spiralling toward Neptune (although it will take billions of years before it reaches the Roche stability limit)



- Phobos is orbiting in the same direction as Mars, but is so close to the planet that its orbital period is less than 1 Martian day. Hence, Phobos is 'outrunning' Mars' tidal bulge, which lags behind. The effect of the bulge is, then, to slow down the moon, causing it to spiral inward.

  Phobos would hit Mars in about 50 million years if it stayed intact, but it will reach its Roche stability limit and break apart before then.

Tidal forces have a major influence on the Galilean Moons

Name	Diameter (m)	Semi-major axis (m)	Orbital Period (days)	Mass (kg)
Io	3.642×10^6	4.216×10^8	1.769	8.932×10^{22}
Europa	3.120×10^6	6.709×10^8	3.551	4.791×10^{22}
Ganymede	5.268×10^6	1.070×10^9	7.155	1.482×10^{23}
Callisto	4.800×10^6	1.883×10^9	16.689	1.077×10^{23}
The Moon	3.476×10^6	3.844×10^8	27.322	7.349×10^{22}
Mercury	4.880×10^6	—	—	3.302×10^{23}

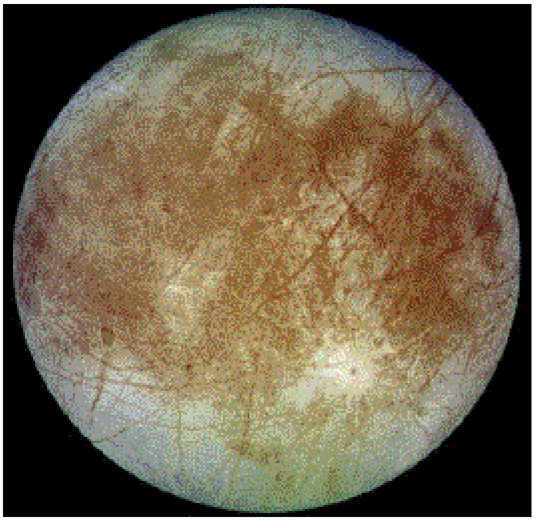
- The orbital periods of Io, Europa and Ganymede are almost exactly in the ratio **1:2:4**. This leads to **resonant effects** :-

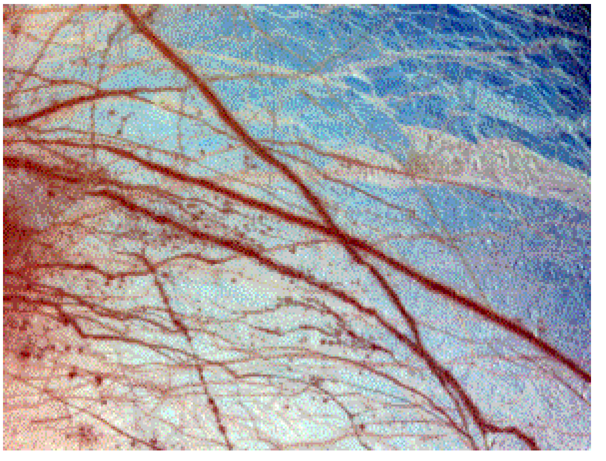
- The orbit of Io is perturbed by Europa and Callisto, because the moons regularly line up on one side of Jupiter. The gravitational pull of the outer moons is enough to produce a small eccentricity in the orbit of Io. This causes the tidal bulges of Io to 'wobble' (same effect as the Moon's libration) which produces large amount of frictional heating.

- The surface of Io is almost totally molten, yellowish-orange in colour due to sulphur from its continually erupting volcanoes.

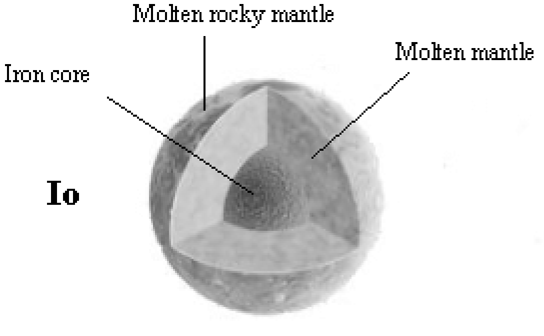
Tidal forces have a major influence on the Galilean Moons

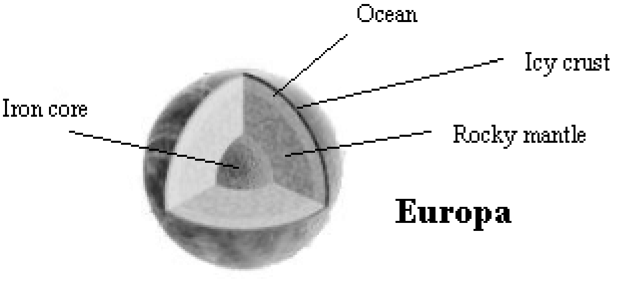
- Tidal friction effects on Europa are much weaker than on Io, but still produce striking results. The icy crust of the moon is covered in 'cracks' due to tidal stresses, and beneath the crust it is believed that frictional heating results in a thin **ocean layer**

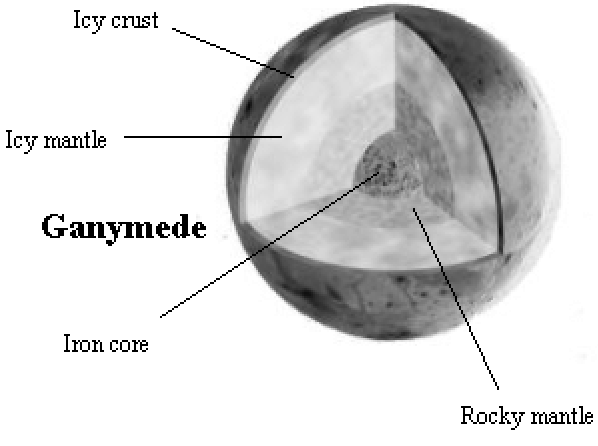


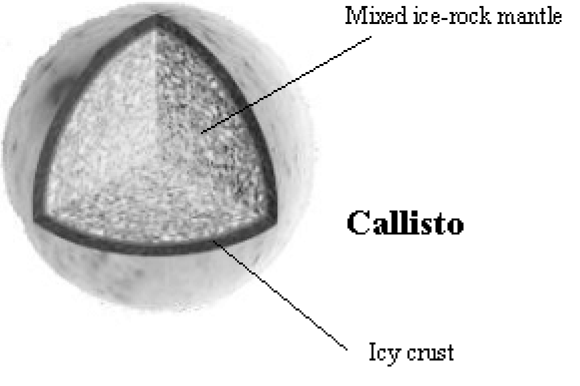


Interior structure of the Galilean Moons









Structure of the Galilean Moons

- The mean density of the moons decreases with distance from Jupiter
- The fraction of ice which the moons contain increases with distance from Jupiter.
- This is because the heat from 'proto-Jupiter' prevented ice grains from surviving too close to the planet. Thus, Io and Europa are mainly rock; Ganymede and Callisto are a mixture of rock and ice.
- The **surface** of the Moons also reflects the history of their formation:

Io:	surface continually renewed by volcanic activity. No impact craters
Europa:	surface young (< 100 million years), regularly 'refreshed' – hardly any impact craters
Ganymede:	Cooled much earlier than Io and Europa. Considerable impact cratering; also 'grooves' and ridges suggest history of tectonic activity
Callisto:	Cooled even earlier. Extensive impact cratering.