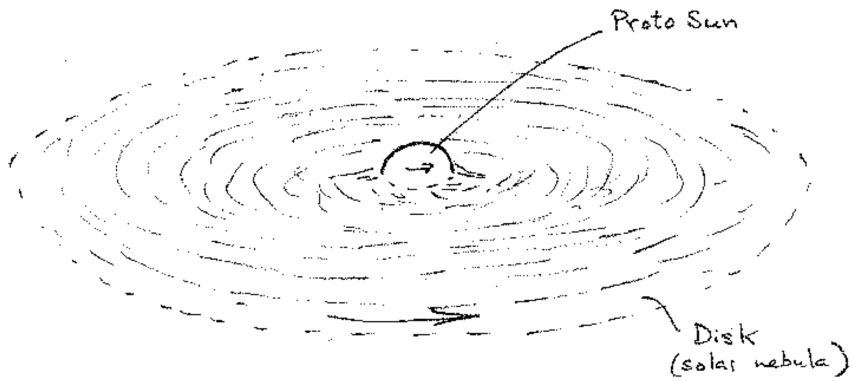
## Tony Fairall - COSMOS COURSE/AST 100F CHAPTER 4
## PLANETS

### THE FORMATION OF THE SOLAR SYSTEM

The major planets follow almost circular orbits, all going around in the same direction and in almost the same plane. This suggests a common origin from a flat disk-shaped gaseous cloud that encircled the Sun. A collapsing protostar needs to shed 'angular momentum' and one possible way is to develop a disk. Such disks appear to encircle a number of newly formed stars observed today. It is therefore very likely that a disk formed around the Sun.




The disk nebula - or solar nebula - was composed of the same material as the Sun, i.e. 98% hydrogen and helium, 2% heavy metals. Isolated from the central heating within the proto-Sun, the disk began to cool. Elements with the highest temperatures of vapourisation, particularly iron and silicates, condensed first, thereby forming swarms of tiny grains within the solar nebula. Like the dust in interstellar space, these grains, although accounting for only a tiny fraction of the mass, would render the solar nebula opaque. Thus, shielded from the heat of the proto-Sun, the cooling in the outer part of the disk accelerated; The condensation of ices may have made the grains sticky since in time they adhered to one another forming tiny bodies or planetesimals. Those bodies that grew large enough used their mild gravitational forces to attract their fellows. In time, each radial zone of the solar nebula became dominated by a single proto planet that used its substantial gravity to sweep up its competitors.

Yet, in competition to the force of gravity were thermal motions. In the outer part of the nebula, the light hydrogen atoms had thermal velocities of a few kilometres per second. Since this was soon less than the escape velocities of the outer proto-planets, the hydrogen was accumulated by those proto-planets - likewise the helium. But in the inner part of the nebula, the thermal velocities of hydrogen and helium were around, ten kilometres per second, greater or equal to the 'escape velocities' of the proto-planets. Consequently the inner proto-planets were unable to draw in hydrogen or helium (other than very small amounts) - even though this was 98% of the mass.

The four giant outer planets are therefore similar in composition to the Sun. The four inner planets, by comparison, are midgets - made almost entirely of the 2% heavy elements. The gaseous remains of the inner solar nebula have long since been blown away.

While this is the generally accepted scenario for the distinction between the four small inner planets and the four giant liquid planets, it has been somewhat thrown by the discovery of large Jupiter-like planets very close to their suns in other solar systems.

Whilst each of the four inner "terrestrial" planets swept up all competitor proto-planets (and a large collision may have knocked the material out of the Earth to make the Moon), no fifth planet came together. Perhaps the radial "zone" was too large for gravity to bring together a single body. Instead that zone is filled by minor planetary bodies - the "Asteroid" belt - of similar composition to the terrestrial planets.

In similar fashion, there is no fifth outer giant planet, but there appears to be a "Kuiper belt" of smaller bodies - icy in composition. Pluto, its moon, and other minor planets so far detected out there seem to be members of the belt. Further out still, there may be a halo - the Oort Belt - a reservoir of small icy bodies that provide the seeds for comets.

The process of the formation of the solar system was repeated on reduced scales as satellite systems formed around the giant outer planets. Obviously such lesser bodies were either heavy elements or icy in composition. Each outer planet today has a ring system - it is not clear whether this is material that never formed into satellites (due to the severe tidal forces) or whether it originates from a satellite that broke up close to the planet.

An empirical relationship, the Bode-Titius law, gives the relative distances of the planets from the Sun:

| Take this series | Add 4 and divide by 10 | Compare to distances from the Sun | |
|---|---|---|---|
| 0 | 0,4 | 0,39 | Mercury |
| 3 | 0,7 | 0,72 | Venus |

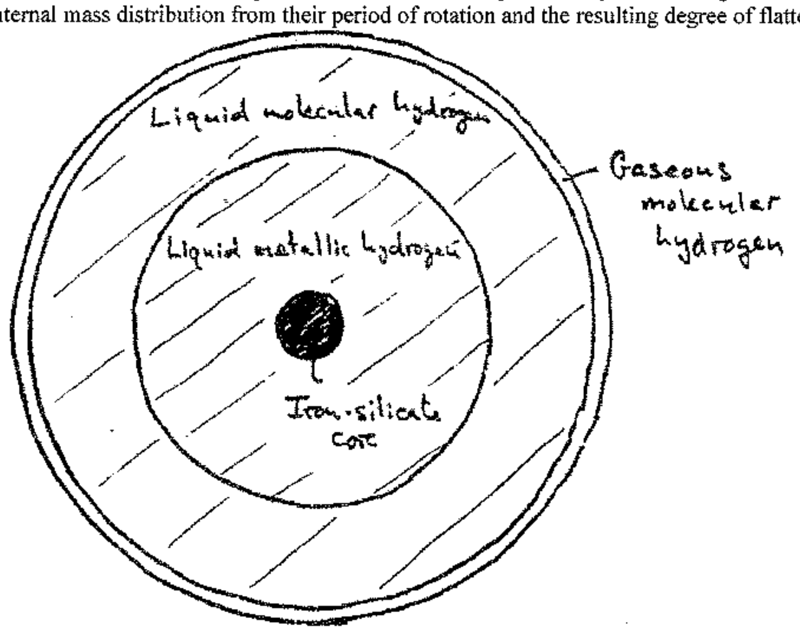
| | | | | |
|---|---|---|---|---|
| 6 | 1,0 | 1,00 | Earth | |
| 12 | 1,6 | 1,52 | Mars | |
| 24 | 2,8 | (Average about correct) | | Asteroids |
| 48 | 5,2 | 5,20 | Jupiter | |
| 96 | 10,0 | 9,54 | Saturn | |
| 192 | 19,6 | 19,2 | Uranus | |

This led to search for missing planet (c 1800), asteroids discovered. Does not work for Neptune + Pluto - very remote.

**THE INTERNAL COMPOSITION AND STRUCTURE OF PLANETS**

The scenario presented above indicates that planets can be classified as either "giant" or "terrestrial" - the latter class can include the large numbers of Moons in the solar system.

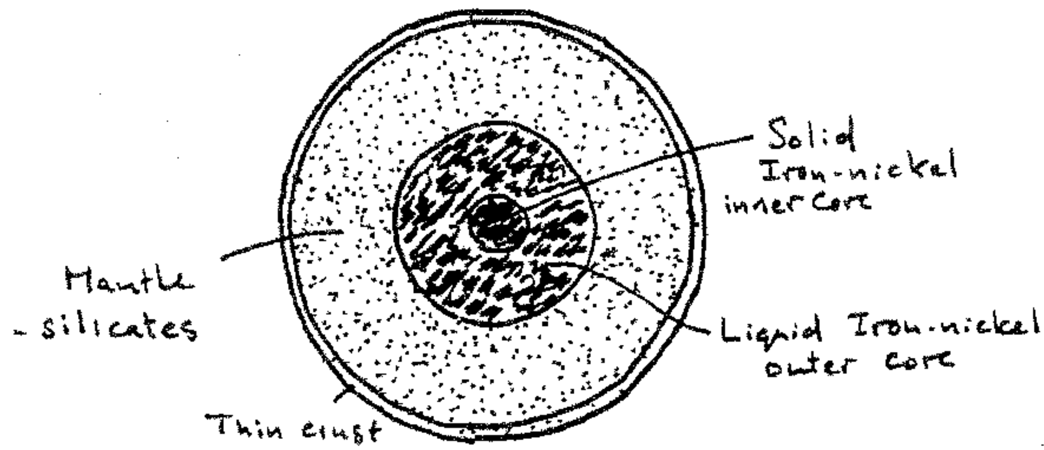
Planets differ greatly in composition - an indication is provided by their average density. It is also possible to gauge the internal mass distribution from their period of rotation and the resulting degree of flattening.



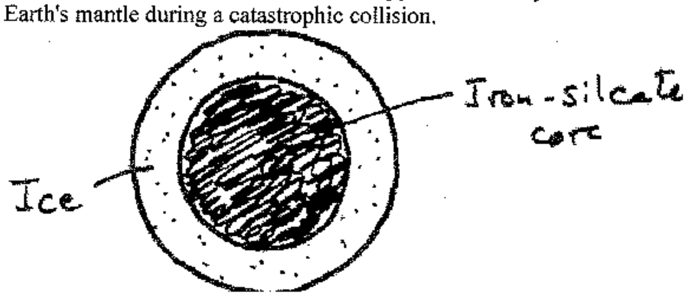

**Giant Planets :** The two largest planets, Jupiter and Saturn, are mainly hydrogen and helium in liquid form (and the description "gas giant", often applied, is misleading) - what heavy elements they have are congregated in the centres. Under the extreme pressures towards the centre, the liquid hydrogen behaves as a metal (i.e. electrical currents can flow in their cores). Jupiter and Saturn are "would-be stars"; their interiors are hot and they radiate out to space about twice the heat they receive from the Sun - although it is obviously in the far infra-red. The flow of heat outward sets up convective motions within the planets' interiors. The details are not understood, but the motions within the metallic region are thought to generate the very strong magnetic fields possessed by these planets.

Uranus and Neptune are much smaller and their interiors much cooler. Some models suggest that their cores could be surrounded by ices.

**Terrestrial Planets:**




The inner planets of the solar system are composed almost entirely of heavy elements - including some radioactive isotopes, with very long half lives. The decay of these isotopes has released a great deal of heat - for example, the centre of the Earth is believed to have a temperature of 6600 K. Under such conditions the interiors are molten and "differentiation" can occur - whereby elements with higher density (chiefly iron and nickel) sink to the centre to form a core (see diagram at bottom of previous page).
Slow convective currents in the core then generate weak magnetic fields (much weaker than those of the giant planets). We would expect Venus to have a core similar to the Earth, but it lacks a magnetic field and its very slow rotation rate does not allow us to gauge its internal mass distribution. Mercury has a large core, almost as if part of its outer mantle had been lost. Mars has a weak cores and the Moon no core. That the density and composition of the Moon seems to match that of the Earth's outer mantle supports the theory that the material used to make the Moon broke from the Earth's mantle during a catastrophic collision.




**Europa, Ganymede and Callisto** (the three biggest moons of Jupiter) lie in a much cooler part of the solar system. They appear to have silicate cores, but surrounded by substantial mantles of water ice (or perhaps water, in the case of Europa and Ganymede). Ganymede is the largest moon in the Solar System, larger even than planet Mercury.
Lying closer to Jupiter, tidal stresses have heated the interior of Io - so much so that it has lost its water mantle and is subject to severe volcanism that is constantly 'turning the moon inside out'.
The density of most of the Moons of Saturn (Titan excluded) Uranus and Neptune suggests that they are almost completely water ice - or rather "dirty ice".
So peculiar is the appearance of Miranda (Moon of Uranus), that some researchers have even suggested that this moon broke apart into a number of pieces and then re-assembled.

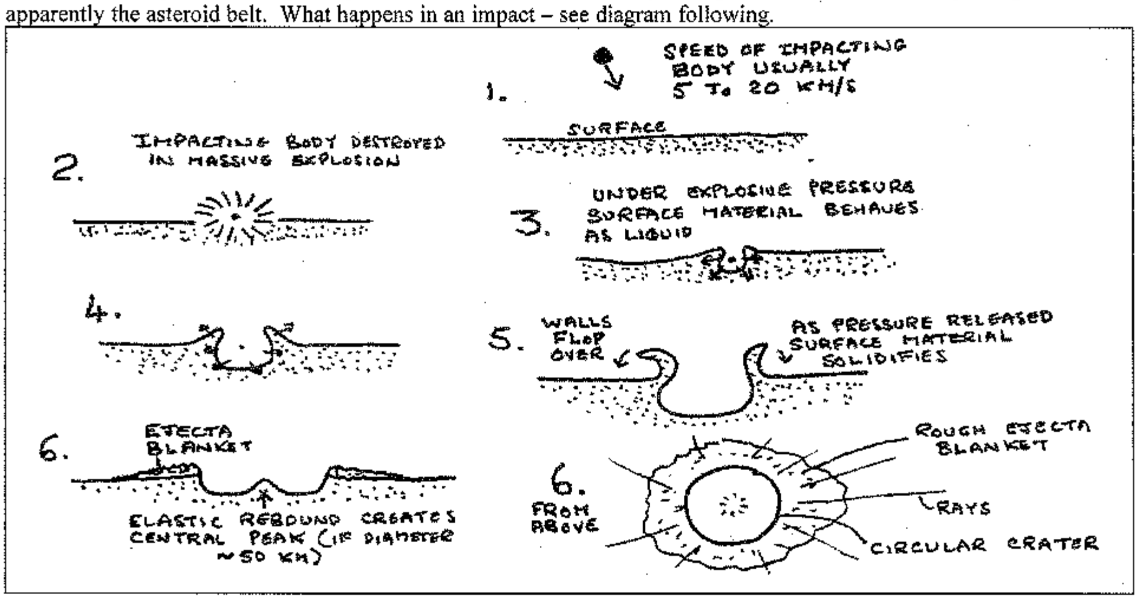
**SURFACE GRAVITIES**
The force of gravity experienced on the surface of a planet varies according to the mass of the planet and the inverse square of its radius. Consequently the surface gravities of the Moon, Mercury and Mars are much lower than the Earth's, while Jupiter's is much higher.

**SURFACE FEATURES OF PLANETS**
The four terrestrial planets and all the moons and minor planets of the Solar System have hard surfaces exhibiting many common features:
Mercury: Very cratered
Venus: Elevated 'continents', volcanoes, some impact craters

Earth: Moving continents, mountain ranges, surface largely sculpted by water, deserts, ice sheets
Moon: Heavily cratered, volcanic maria
Mars: Elevated southern hemisphere heavily cratered, desert, ice sheets
Io: Volcanoes
Europa: Ice covered ocean
Ganymede: Thick ice cover
Callisto: Heavily cratered
Titan: Dry rivers and lakes
Triton: Icy geysers

**IMPACT CRATERING AND ITS DECLINE**

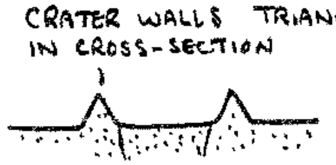
Impact craters are the most ubiquitous of surface features on planets. Some planets, like the Moon, have so many impact craters that there is no place on their surface that is not an impact crater, and newer craters obliterate older craters. As such they represent the 'sweeping up' of minor bodies in the solar system. Their ages confirm that most of the cratering (including some major impacts) took place during the first billion years of the solar system. The cratering rate has declined dramatically as the population of minor bodies was decimated. However, even today, cratering continues - though the last major impact on Earth was about 50 000 years ago. The source for the impacting material is apparently the asteroid belt. What happens in an impact – see diagram following.

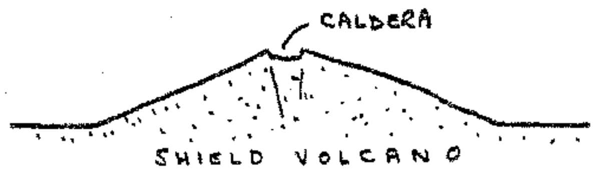



All planets must have received similar numbers of impacts - yet on some planets, erosion has removed the craters. The Earth, with only one intact impact crater (in Arizona), is an example of severe erosion - though Io has none. Many planets, like Venus or Mars, show limited numbers of impact craters - the southern hemisphere of Mars has much less cratering than the Moon, while Venus only shows cratering from the last half billion years. Thus the degree of cratering on a planetary surface can be used as an indication of the age of the surface (the heavier the cratering, the older surface).

**VOLCANISM**

Volcanic vents emit lava and gas (gas will be dealt with later). Thick lava builds elevated shield volcanoes, especially on Venus, Earth and Mars. The largest is Olympus Mons on Mars - almost 25 km high.




Thinner lava seems to have gradually flooded large impact basins, forming 'maria' basins - the most conspicuous features on the Moon's near side - also found on Mercury and Mars. The flows are complex - building up over millions of years. The thin lava comes to the surface either through fractures or from craters that mimic impact craters, but are different in their cross sections (see diagrams)
High speed ejection (~1 km/s) is constantly occurring from several volcanoes on Io. Much sulphur is emitted and rains down on the surface almost completely covering the planet. Lakes of hot liquid sulphur and lava flows are apparent; it seems that the underlying mechanism must be different to terrestrial volcanoes.

**STRATIGRAPHY**
This concerns the relative chronological sequence of surface features and is particularly applicable to the Moon and Mars. A newer feature will cover or partially obliterate an older feature. Also older craters are more subdued and dark. Fresh craters show sharp profiles, rugged appearance, light materials or ray systems.

**EROSION**
Planets with no atmosphere suffer bombardment from tiny meteors, which tends to pulverise surface layers - hence making a 'regolith' resembling dry Portland cement. It also contains stones and microscopic glass beads (solidified from drops of molten material flung skyward during impacts). The beads are an excellent light backscatterer (esp. rays from craters on Moon best visible near Full Moon).
Planets with some atmosphere - wind erosion results from abrasive action of suspended particles. Sand shifts with wind patterns, but collects to form dune fields in low lying basins.
Water - This is by far the most powerful erosive agent. The surfaces of the continents of the Earth are subject to severe water erosion. Smaller features (e.g. impact craters) are rapidly erased, even major mountain ranges only survive for perhaps only a tenth of the Earth's lifetime. Sedimentary basins; later elevated, are significant features (e.g. Karoo).

**VALLEYS AND RILLES**
Rivers rapidly carve valleys or, in dryer climates, canyons with characteristic dendritic pattern - esp. Earth, Mars and Titan. The climate of Mars is currently so cold that virtually no water exists in liquid form; apparently it was warmer in the past. The surface of Titan is so cold that water only exists as hard 'rocks', but liquid methane was probably responsible for the valleys and lakes (now dry).
The Moon, Venus and Mars possess many valleys clearly not made by running liquid, at least not on the surface. Rilles - some straight and some sinuous - are somehow related to volcanism, partly by collapse.
Africa has a giant rift valley where the continent is currently splitting into two pieces. Mars has gigantic rift valley (Valles Marinus), thousands of kilometres long and up to 6 km deep, a great split in its surface. In places it is modified by water erosion, but it is mainly growing by the surrounding elevated plateau collapsing.

**WATER AND POLAR CAPS**
These are abundant stores of water ice. Mars had a wet episodes in its past, the low lying northern hemisphere (devoid of ancient craters) may have at times been a shallow ocean. Currently Martian water is frozen in the soil, and thick layers of ice appear to have accumulated at the poles. These are covered by sand. The conspicuous white polar caps on Mars that grow and shrink with the seasons are formed from thin coatings of carbon dioxide (when about a quarter of the Martian atmosphere condenses). Earth has ice caps kilometres thick on Antarctica and Greenland.

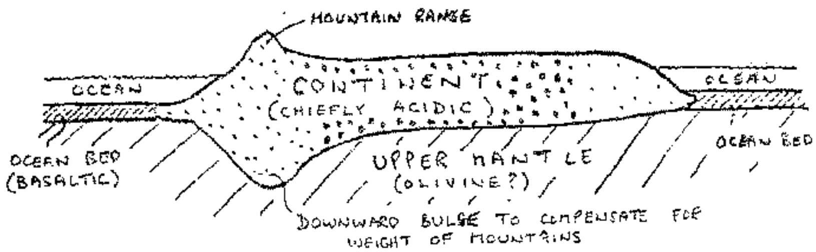
**CRUSTAL MATERIALS**

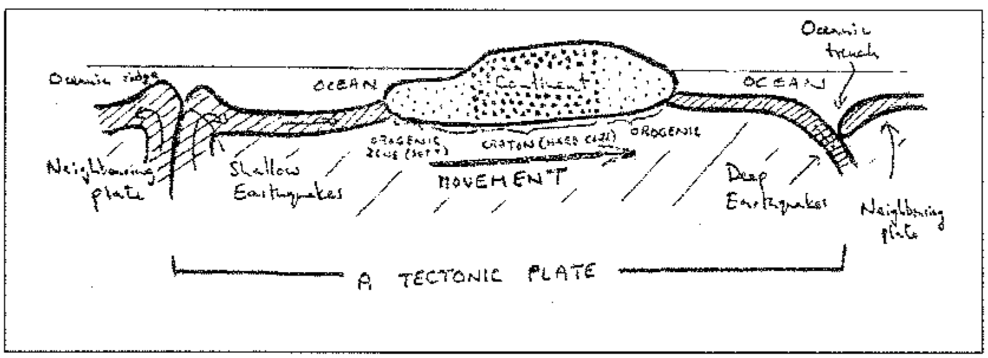
The crusts of terrestrial planets are predominantly silicates. Silicon atoms are usually linked by oxygen atoms (silica - acidic), otherwise metal ions intervene (olivines - basic). There are intermediate cases, such as feldspars and pyroxenes. There is a general tendency for original crustal materials to be acidic or intermediate. Materials deeper down, brought up in lava, tend to be basic. The marias of the Moon are basalts (basic) rich in iron and titanium. Materials elsewhere on the Moon are complex - usually feldspathic breccias (partial melting and recrystallization) as expected from impact ejecta. Mars also has basalts. The high iron content in Mars' crustal materials gives its rocks and sand a reddish colour.

**CONTINENTS**

Both Earth and Venus have continents - bodies of material elevated above the surrounding crust - apparently masses of lighter material being in isostatic equilibrium and floating higher. On Earth, it is of course the continents that generally project above the surface of the oceans (see diagram).

Most continents have a hard core termed a craton (heavy stippling in diagram) surrounded by softer orogenic zones (light stippling),



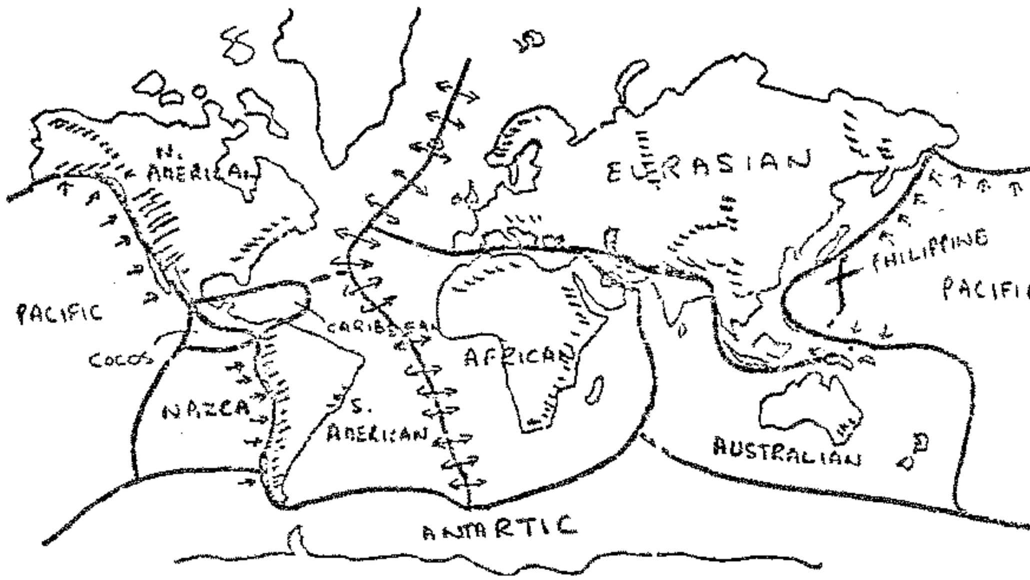




**THE TECTONIC PLATES OF EARTH**

The thin ocean beds are not permanent but are constantly replenished and replaced by new material from the Earth's interior. The new ocean bed pushes and spreads sideways from mid-oceanic ridges. Old ocean beds are subducted back into the Earth's interior in deep trenches close to the continents. The surface of the Earth is fragmented into segments, the tectonic plates (see diagram).

The continents ride with the plates sometimes separating and sometimes colliding with one another - the soft orogenic zones getting crumpled and the continents getting sutured together (e,g. the collision between India and Asia causing the Himalayas - a collision still in progress!). The Urals were formed when Europe and Asia were sutured, the Appalachians when Africa and North America collided.

At intervals of a few hundred million years, the continents tend to gather into a single supercontinent. Some 300 million years ago, most of the continental masses came together to form Pangea. Pangea became unstable, possibly




because too much heat built up beneath it, and split into Laurasia and Gondwanaland. Laurasia split into North America and Eurasia, Gondwanaland into South America, Africa, Antartica, India and Australia. Africa is soon to split again (along the rift valley). The Atlantic Ocean (only -150 million years old) is rapidly opening up - the Pacific is being closed on all sides - its plate is slowly being subducted. In less than another 200 million years, this is where all the continents will regroup to form a new supercontinent. And so the cycle will repeat, as it must have already done so many times in the Earth's history.

Note that oceans are relatively shallow over the mid-oceanic ridges where new material comes up. The mid-Atlantic ridge actually rises above sea level at one point - Iceland.

One other place of interest is California where the infamous San Andreas fault marks the boundary between the Pacific plate (moving laterally to the north) and the N. American plate (moving to the south).

The Earth is, of course, the only planet known to have this plate motion.

**THE PRIMARY AND SECONDARY ATMOSPHERES OF THE TERRESTRIAL PLANETS**

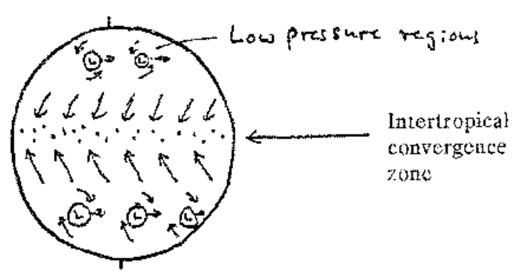
The Primary atmosphere formed with the planet - hydrogen and hydrogen compounds (methane, ammonia etc.) - but was gradually lost to space because the thermal molecular motions approach escape velocity - especially molecular hydrogen and helium (Moon - gravity too low to retain any atmosphere, Mercury - virtually the same).

The secondary atmosphere, formed from outgassing from the crust (volcanism), is almost entirely carbon dioxide - as in atmospheres of Venus and Mars - with a small amount of nitrogen.

The Earth has lost 99% of its atmosphere - almost all carbon dioxide washed out by rain to form carbonate rocks. Only nitrogen remains, plus oxygen from plant photosynthesis.

**WEATHER**

General planetary circulation
(surface)



Hot air rises where insolation is greatest (near Equators) and descends at higher latitudes. This circulation is forms 'Hadley' cells (Earth and Venus). On Earth, variations in weather are largely driven by the heat stored in the oceans. Both Earth and Venus show weather patterns rotating faster than the planet.

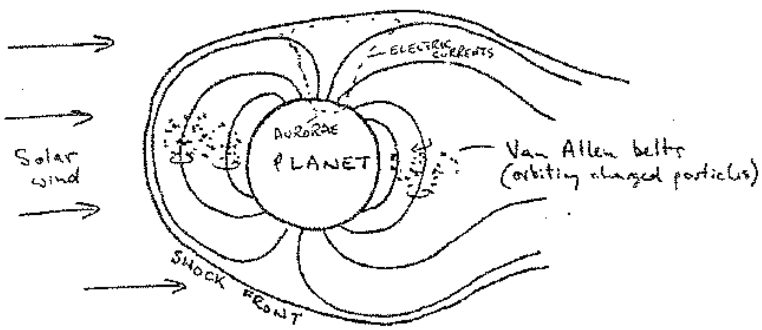
Violent atmospheric motions can occur if substantial energy can be directly inserted into atmosphere: Water condensing releases large latent heat -drives thunderstorms, hurricanes etc. Dust particles suspended in atmosphere absorb solar heat directly - sandstorms. (In 1971 and 2002, the whole of Mars was covered by a single sandstorm).

**ATMOSPHERES OF THE GIANT PLANETS**

The gaseous outer regions are, of course, mainly hydrogen and helium. However, a variety of other components create cloud layers and colours. The deep blue colour of Neptune is from Methane absorption, but the reddish colours in the clouds of Jupiter and Saturn are not yet explained.

Rising convective motions push clouds higher (lighter bands on Jupiter and Saturn), sinking motions make clouds lower (darker bands on Jupiter and Saturn) - but why these should form longitudinal bands, each rotating at a speed different to each other, is not properly understood. The driving forces may be cyclonic storms - the most conspicuous being the great red spot of Jupiter (which has been there since telescopes were first used) the great dark spots of Uranus and Neptune and the white spots on Jupiter and Saturn (which come and go). How these storms are powered is not known.

**PLANETARY MAGNETOSPHERES**




Planets with magnetic fields (Mercury, Earth, Jupiter, Saturn, Uranus and Neptune) are surrounded by magnetospheres. The stronger the field, the more extensive the magnetosphere. Magnetospheres are bounded and deformed by the solar wind (charged particles) blowing past. Surges in the solar wind may compress the magnetosphere and set up massive electrical currents (causing aurora displays).

Magnetospheres serve as a shield to cosmic rays - but such charges particles tend to accumulate in particle belts (van Allen belts). Such regions are dangerous to humans and (in the case of Jupiter and Saturn) even spacecraft.

Jupiter: Io (innermost of Galilean moons) moves through magnetosphere and stirs up particle belts causing radio radiation.

**LESSER BODIES OF THE SOLAR SYSTEM - ASTEROIDS AND METEORITES**

Tens of thousand of minor planetary bodies, concentrated in the asteroid Belt, have been detected. Towards 20 000 asteroids with known orbits are (named and catalogued. They avoid orbits with periods 1/2, 1/3 etc. of Jupiter's period - the 'Kirkwood Gaps' (likewise gaps in rings of Saturn due to innermost moon). Exception - the 'Trojan' asteroids - have same period as Jupiter but keep 60 degrees ahead or 60 degrees behind the planet,

A few "Apollo" asteroids have eccentric orbits that bring them within the Earth's orbit - it is not known what perturbed them into such orbits. In a relatively short time (~million years) they will collide with one of the inner planets. Smaller examples of "Apollo" asteroids are large meteors which survive the fiery passage through the Earth's atmosphere. Once landed they are termed meteorites.

Different types:

Stones (Chrondites) 86% of meteorites
Stone (Achrondrites) 7%
Stoney-Irons 2%
Irons 5%

These statistics apply to those seen to fall. In comparison, most fallen meteorites discovered are Irons - by far the easiest to recognise or detect.

The iron meteorites must be fragments of a larger body or bodies - sufficiently big for differentiation to have occurred. The achrondrites may be the mantle fragments.

Chrondrites are characterised by tiny round bodies, chrondrules, packed together in a grey silicate matrix. Chrondrules vary in size from that of a pinhead to a pea. Their presence implies no differentiation and it is possible that they are original planetesimals.

## LESSER BODIES OF THE SOLAR SYSTEM - ICY BODIES AND COMETS

There is apparently a vast reservoir of small icy bodies in the Kuiper Belt and Oort Cloud. On occasions, these are somehow perturbed and fall in towards the Sun. They follow a virtual parabolic orbit around the Sun and return to the outer regions. In certain cases, an encounter with a planet may slow down the body such that it ends up in a short period eccentric orbit - such as the nucleus of Comet Halley with a period of only 75 years.

These object are low density, partly fluffy in composition. Once described as 'dirty snowballs' the 2005 impact of a spacecraft with Comet Tempel 2 indicates that 'snowy dirtball' might be more appropriate.

During the time when the body is close to the Sun, the heat of the sun sublimates the ice (turns directly into water vapour). Hampered by the build up of rocky debris on the surface, the water vapour so formed may blast out through crevices in the crust carrying finer particles with it. Halley has now shrunk to about 11 x 7 km in size and probably loses about 6m of surface ice each perihelion passage. Other cometary nuclei that pass closer to the Sun may not even survive the passage intact. The water vapour and dust form a spherical tenuous "coma", sometimes millions of kilometres across. This is the visible comet. Dissociation of water molecules releases hydrogen that forms an even larger cloud. From the fragile coma, two forms of tails develop. Solar radiation pushes the dust to form an amorphous yellow tail. The solar wind drives ionised gas to produce a structured blue tail. Obviously, both tails point away from the Sun.

Eventually in place of the comet, will be simply a swarm of particles. At times the Earth has encountered such swarms (they can even be predicted) and a meteor shower is observed. Since they all come from a common direction, they will appear to come from a common radiant in the sky. None of these particles is large enough to reach the Earth's surface.

Collisions can occur. At least one comet (Shoemaker Levy 9) was captured in orbit around Jupiter and eventually collided with that planet. It is not known if the explosion in the atmosphere over Siberia in 1908 was caused by the impact of a small comet or asteroid. Many comets fall straight into the Sun.

## EXTRA-SOLAR PLANETS

Solar systems such as ours are believed to be common. Possible almost every star may have some form of planetary bodies. Currently, more than 150 planets have been detected orbiting other stars.

Planets and their host stars orbit around their common centre of gravity, usually located within or very close to the parent star. For example our Sun moves in a circle at 16 metres a second as Jupiter (by far the most massive planet in our Solar system) orbits around it. By looking for such oscillations of other stars, we can indirectly detect orbiting planets. The technique obviously favours massive Jupiter-like planets close to their parent stars, and these are the majority found.

However, some extra-solar planets have been found because their orbits are seen edge-on and they 'eclipse' their parent star, causing a small drop in the light we receive.

One of two extra-solar 'planets' have even been directly imaged, but they are more likely brown dwarfs – very low luminosity stars.