8. The Terrestrial Planets - Internal Structure

Interiors of the other terrestrial planets

MARS

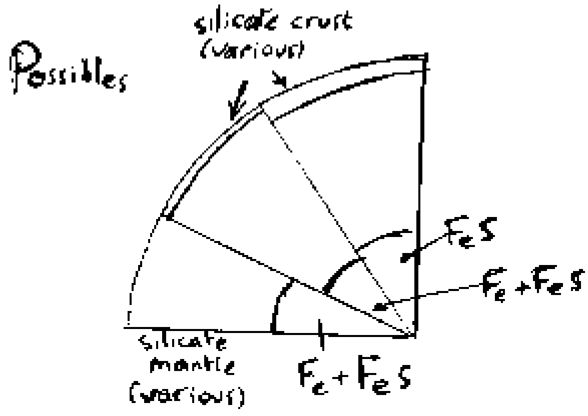
The Martian day is very nearly the same length as the terrestrial day - 24h 37m and 22s. Mars has an orbital eccentricity of e = 0.0934, which is much larger than earth and Venus. This makes a substantial difference to the sunlight received at perihelion and aphelion - $(1+e)^2/(1-e)^2$ is around 1.4545. i.e a 45% difference. This has a considerable effect on its climate.

Mars has two natural satellites, Phobos and Deimos. It also has a Trojan asteroid companion - 5261 Eureka, a 2 km diameter body. Phobos orbits inside the synchronous altitude (i.e. it rises in the west and sets in the east), and is gradually spiralling in. Deimos orbits outside the synchronous altitude and is gradually spiralling out. The orbital periods and semi-major axes of these satellites mean we can determine M_M, which is about 0.01076 M_E. This gives a mean density M_M/V_M of 3940 kg m^{-3} (compared to earth's 5524). The difference with earth is not as great as it sounds, since earth is much more compressed by self-gravity. If we calculate the uncompressed densities we get 3700-3800 kg m^{-3} for Mars and 4000-4500 kg m^{-3} for earth. Thus, they are probably not of startlingly different compositions.

J_2 from Phobos/Deimos orbit tracking gives C, the moment of inertia about the spin axis. C/MR2 is about 0.365. (Remember we would expect about 0.4 for a uniform body). There are probably some surface effects contributing to this, especially the "Syria Rise", but generally it is believed this shows a rise of density towards the centre beyond what would be expected from compression alone. Thus the planet has experienced differentiation in its geological history.

With the advent of Mars probes we have J values now to at least 12th order in both latitude and longitude. Unfortunately, despite the Viking landings we do not have seismic data. Viking 1's seismometer did not deploy, and Viking 2's was mounted poorly so that one cannot tell seismic effects from wind and atmospheric effects.

There is speculation over the interior, with various models having been developed to explain the density and other data. It is suggested that the Fe to Si ratio should be about the same for earth, Mars and Venus (see lectures on solar system origin) - i.e. about 1. It is also expected that Fe will become more oxidised with heliocentric distance. After differentiation, this would lead us to expect Mars to have a denser mantle and a less dense core than the earth. This fits in with earth. This fits in with the determination of C. The core may be a Fe-FeS eutectic. An FeS core is plausible but we do not really have enough information. Possible structures that fit the data we have can be made with varying proportions of crust and mantle and core, and with varying compositions of core:



A key piece of evidence when considering the core is whether or not Mars has a magnetic field. The early Mars probes saw a bow shock at around 5000 km radius which implies a balance of solar wind with an iono- or magneto-pause at 25 gamma. This implies a very small magnetic field, if any. The upper limit after allowing for gas pressure would be of the order 10^{-5} of the earth's. It has only been with recent probes that a very weak magnetic field has been confirmed. This is so weak it cannot prevent ingress of the solar wind into the upper atmosphere, so the boundary is little different from an ionopause.

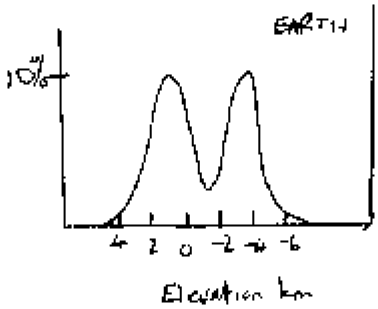
A pure Fe or Fe-Ni core would be solid. An FeS core, or better still an Fe-FeS mix, would melt at Fe-FeS eutectic temperatures and so would allow it to still be partly molten. It is still a matter of conjecture whether the **B** field seen requires a liquid core.

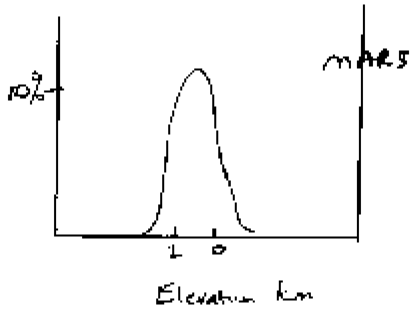
The detailed gravitational potential structure suggets that the crust is well-compensated on large scales, but some "small" (locally large) features, especially the large volcanoes acially the large volcanoes are uncompensated - that is they erupted late in history and settled onto a thick, cold crust. The height of Olympus Mons, the largest volcano in the solar system, is 27 km to the caldera (the rim of the summit crater). The great height suggests either very light magma was extruded, or the base of the magma column must have extended to very great depths. The weight of fluid magma is in balance with hydrostatic pressure exerted by the nearby solid mass of the volcano:

$$d_{crust} g_{Mars} H_{crust} > d_{magma} g_{Mars} H_{magma}$$

where H_{magma} is the height of the magma column and H_{crust} is the thickness of the solid crust (lithosphere), and d is the density. For extrusion of magma, the pressure due to the height of the extruded column must be less than that due to the weight of crust displaced. Therefore the density of the magma must be less than the crust to get eruption. Long surface flows suggest low viscosity - i.e. basalt rather than dense magma - and this in turn suggests an extremely deep magma source and a very thick crust. The mobility of the lava is also evidenced by the large numbers of collapse craters at the summit of Olympus Mons.

Some tectonic activity seems to have taken place, though its significance is disputed. Some may be associated with changes in orientation of the spin axis, others may be tensionis, others may be tensional. Many are local, and some are not easy to explain. "Continental drift" and plate tectonics as such are ruled out. A "hypsogram" (elevation distribution) of Mars is unimodal:





This is in contract with the earth which is bimodal due to the thick-continent/thin-seafloor nature of the crust.

Some areas of Mars are heavily cratered by impacts. The surface has a heavily cratered southern hemisphere, and a smoother, volcanically in-filled northern hemisphere. (The first Mariner photos of Mars thus gave the false impression of a totally lunar-like landscape.) There is some "chaotic terrain" from slumping and collapse on a grand scale. Light areas of the surface are bright, whereas the lowlands are a mixture of bright and dark. Much of the contrast is known to be due to the settlement of wind-blown dust. Olympus Mons is one of a chain of extremely massive volcanoes.

The heavily cratered terrain is very old - 3-4 10^9 years old. (This is by crater-count dating, making assumptions about asteroidal and cometary flux histories.) The large volcanic constructs, on the other hand are believed to be only 300m years old. Thus we have an old, cratered southern hemisphere and a newer northern hemisphere surface with volcanoes and large plains. There is evidence of water in the planet's early history with dendritic (root-like) valley sysitic (root-like) valley systems typical of water flow, plus wide flood-cut channels up to 2000 km long. Whether or not this required large bodies of surface water to have been present is still a matter of conjecture. The volcanoes seem to be evidence of past "hot-spots" on the planet.

Viking Landers

The Viking Landers gave us our first detailed view of the surface.

Viking 1 landed in volcanic terrain in the Chryse region. It was broken and blocky terrain with signs of faulting and impacts, with weathering by formation of a Ferric Oxide stain and iron-bearing clays. There were drifts of fine grain dust over much of the landscape.

Viking 2 landed near the crater Mie in Utopia Planitia in the outskirts of the ejecta debris. The area was flat and rich in wind-transported sediments. There was a moderately dense and uniform coating of boulders of about 1m in width. Most rocks were vesiculated (i.e. filled with voids) which could be due to gas bubbles in volcanic extruded lava or solvent extraction of water-soluble components. There were clods of dust, loosely cemented, and thin sheets of apparent "duricrust" held together by a chemical sediment such as calcium sulphate (whicih also forms a cement in terrestrial deserts).

There was a high proportion of Fe and S, the latter some 10-100 times that found in terrestrial rocks. There was some Ca, Al and Si with small amounts of Ti. There was a high Ca:K. There was a high Ca:K ratio. The overal suggestion was of 80% iron-rich clays, 10% Mg_2SO_4 and 5% each of calcite and higher oxides of iron like haemetite, goethite and maghemite. The material was not dissimilar to what was seen in CI chondrites. The water content was unresolved, but the presence of Goethite is interesting as it is unstable on the surface at daytime and undergoes the reaction 2 FeOOH => Fe_2O_3 + H_2O, i.e. it turns into haemetite. Infra-red spectroscopy of the surface suggests the presence of limonite, a mixture of goethite and haemetite, and it has been suggested that this what gives Mars its red colour. There may only be a fraction of this in the surface material, though.

The SNC Meteorites

We have another source of material from Mars, and one which we can examine in the laboratory. There is a group - or rather 3 groups - of meteorites believed to originate on Mars, known as the SNC Meteorites. The SNC refers to the names of the 3 sub-groups: Shergottites, Nakhlites and Chassignites (each named after the first example of each found). These are young compared with other asteroidal material (800Myr to 1.3 Gyr) and contain shock-melted glasses. Because the material in the rocks has been differentiated and shows signs of heating, it is fairly certain t he rocks had to come from a fairly large body. Dynamically it is difficult to see materidifficult to see material reaching the earth after being thrown off satellites of the gas giants. It is unlikely, even ignoring their ages, that asteroidal material could have been hea ted enough to form the rock, so that leaves Mercury (ruled out really because of the problems with the dynamics of reaching Earth from that far in to the sun), Mars, Venus and the Moon. Even Venus is problematic dynamically, but the strongest piece of evidence that they came from Mars is given by the isotopic abundances of the gases. Trapped within them are traces of gas which can be analysed, and it is the isotopic composition Of this which leads us to conclusions about their origin.

The 12 SNC meteorites have isotopic abundances of Neon, Argon, Krypton and Xenon - the noble gases which have not combined with other elements and so give a clue to the originating materials of a solar system body (see the section on soalr system origins) - which are peculiar to Mars as measured by the Viking Landers in the Martian atmosphere. There are also unusual isotopes of Argon and Xenon which match Viking measurements. Besides the noble gases, the relative abundances of O18 and O17 are also unique to the Martian atmospheric measurements of Viking.

Other things which are additional evidence includes a common abundance of Iron Disulphide and trivalent iron in these bodies.

Recently there has been a lot of publicity surron a lot of publicity surrounding a meteorite known as ALH84001 (Allen Hills, Antarctica, found in 1984). This Martian meteorite has been examined minutely due to the suggestion that the presence of some strange microscopic features and particular carbon-based compounds suggest a biological origin. We shall not enter into that controversy, but it is intersting to note that ALH84001 was classified a Martian meteorite because of the tell-tale gas isotopic abundances described above for the SNC meteorites. It also shows the abundance of iron disulphide and trivalent iron, but interestingly it appears to be older than the others - 4.5Gyr, which places its creation near that of the solar system. It was presumably incorporated into Mars soon after creation by accretion, and only lost due to meteoritic collision or some similar mechanism some time later.

VENUS

Venus has no natural satellites, so before the days of space probes it was not easy to get an accurate determination of its mass. In recent years, however, this has changed, with a number of orbiters and landers visiting the planet, so we now know GMV fairly accurately, along with the J2, C etc terms.

The mass of Venus is 4.871 x10^{24} kg (0.851 ME) and its equatorial radius (Requ) is 6051.3 km.

It rotates retrograde in 243.01 Earth days and has an orbital period of 224.7 earth days, sod of 224.7 earth days, so there are 2 solar rises and falls per year. (The Venus day is 116.75 earth days long.) Another way of looking at this is that it rotates almost 4 times as seen from Earth per inferior conjunction, and 5 times as seen from the Sun. The slow rotation rate has lead to speculation about the superrotation of the atmosphere counteracting the tidal effect to leave the residual rotation. The J_2 term is very small for Venus. It is difficult to see if this is because the rotation rate is low (so the centrifugal bulge has not been raised) or if it has been the reason why there is some rotation still, the tidal damping being so small. (An alternative theory is that the planet rotates retrograde following a collision with an asteroid.)

There is no seismic data on Venus - landers have not lasted long enough in the searing heat and immense pressure to do more than take a few photos and make preliminary soundings of the surface rocks. The deduced density is around 5.245 kg m^{-3}, around 5% less than the Earth's. Thus the \uncompressed density of the original material was about the same and so one speculates there might be about the same structure and composition as the Earth (i.e iron core, silicate and oxide mantle). It is assumed, for example that the planet is completely differentiated.

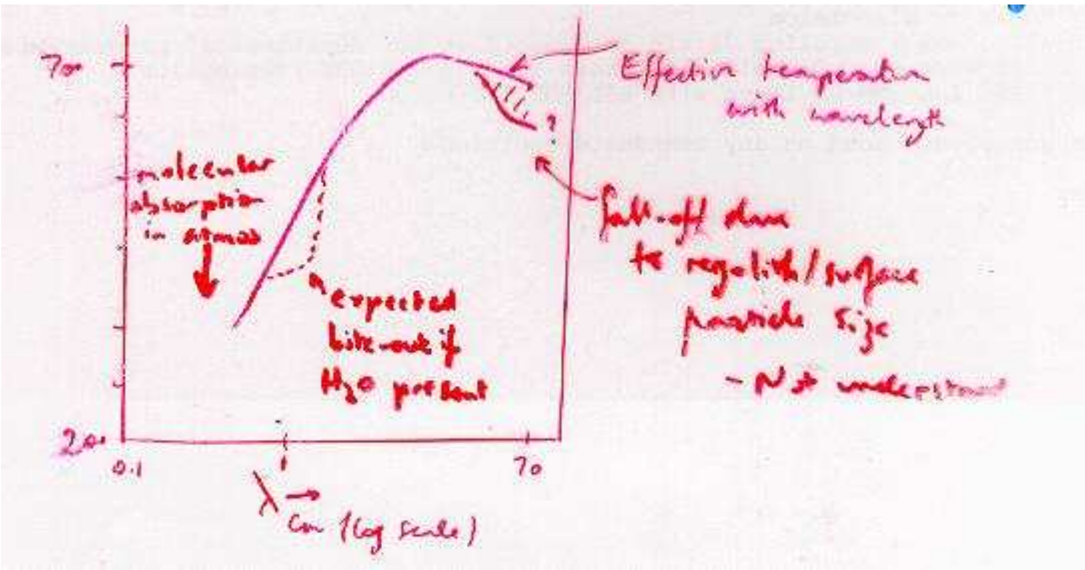
There is thus no enrichment of iron compared to the Earth - in fact it goes against the trend of tgainst the trend of there being a higher proportion of iron the nearer the planet is to the Sun.

Geochemically plausible models are compatible with there being a core-mantle boundary at about 2800 +/- 100 km depth. There is no detectable magnetic dipole, with B less than about 0.00005 of the Earth's. One might expect this in some ways, since the spin rate is so slow, but the amount of spin there is would be expected to generate a dipole larger than that if there was a comparable structure to the earth. The reason for this is a matter of conjecture and range from there being a solid core, to there being a mantle which is solid to the core. Since the theory of the Earth's dynamo still is not entirely worked out, it may be that there is something about the Earth dynamo that we do not fully appreciate which is missing here - could it be that there is no solid inner core and this is necessary for the dynamo? No solid core would be understandable. Perhaps Venus is just that little bit too small to have sufficient pressure at the centre to have a solid core. Alternatively maybe there is no definite core/mantle divide - though this would be difficult to reconcile with the density structure.

J_2 is around 1/200 of that of Earth (+/1 40%) - hence the comments about the small tidal bulge and the small tidal effect from the Sun mentioned about. The surface consists of 65% plains, 8% highlands and 27% lowlands. Tds and 27% lowlands. The largest mountain is Maxwell Monte, which is 12 km high. There is some evidence of plate tectonics, with Western Aphrodite Terra being the site of some crustal spreading (several cm per year). Other regions show deformation due to compression and convergence. However it is fairly certain that continental drift as the Earth knows it is unknown. The surface has been mapped in sub-kilometer detail by radar on an orbiting satellite (Magellan) (necessary of course because the surface is otherwise shrouded in clouds).

The surface seems close to isostatic equilibrium, so maybe there is a fairly thin lithosphere/asthenosphere. There are some constraints on surface chemistry from the atmosphere, though this is a complex subject - see Lewis pp. 459-462. A little is known of the surface rocks from the sampling carried out by the Soviet Venera probes - this generally shows basalts, probably of volcanic origin.

Emission profiles of the planet show that its black body temperature varies with wavelength due to absorption by the atmosphere. This is shown in the graph of effective temperature against wavelength, where wavelength varies between 0.1 and 70 cm:



Note that the expected bite out in the profile that should be present if there is water in the atmosphere does not appear, suggesting the atmosphere is virtually devoid of water vapour. Tly devoid of water vapour. The larger wavelengths penetrate the atmosphere and come from the surface. The shape of the graph there tells you something about the regolith and particle sizes, though this is largely not understood.

Cratering is seen extensively in some areas, though there is less cratering than might be expected. This is probably due to the dense atmosphere. The smallest bodies burn up. The intermediate bodies tend to break up and fall as a close-packed shower. Only bodies >1 km diameter actually impact, and the dispersion of secondary ejecta is suppressed. All this ties in with the tendency for Venusian craters to be large and/or grouped together.

MERCURY

Mercury has a mass of 0.056 ME. This has been determined from the pass of the EROS asteroid and refined by the flyby of Mariner 10, since it has no natural satellites to give the relevant period/orbital radius data. It takes 58.64 days to rotate about its axis, and there is an exact 3:2 ratio between its orbital and axial rotation rates (sidereal). Thus one side of its long axis faces the Sun at every other perihelion.

Mercury's density is very high. Its radius is 2440 km, so its density is 5430 kg m-3. This is between the values of Earth and Mars, but this is largely uncompressed, suggesting there must be a large iron core over a silicate mantle. (Models suggest 80% core and a silicate mantle, though t silicate mantle, though there could be less silicates and more FeO and FeS in the core. Why should it be so dense? This is presumably because it was formed after the most volatile material had been dispersed from near the Sun by solar heating in the early solar system; an alternative explanation could be that it was in collision with another body which left only its core.

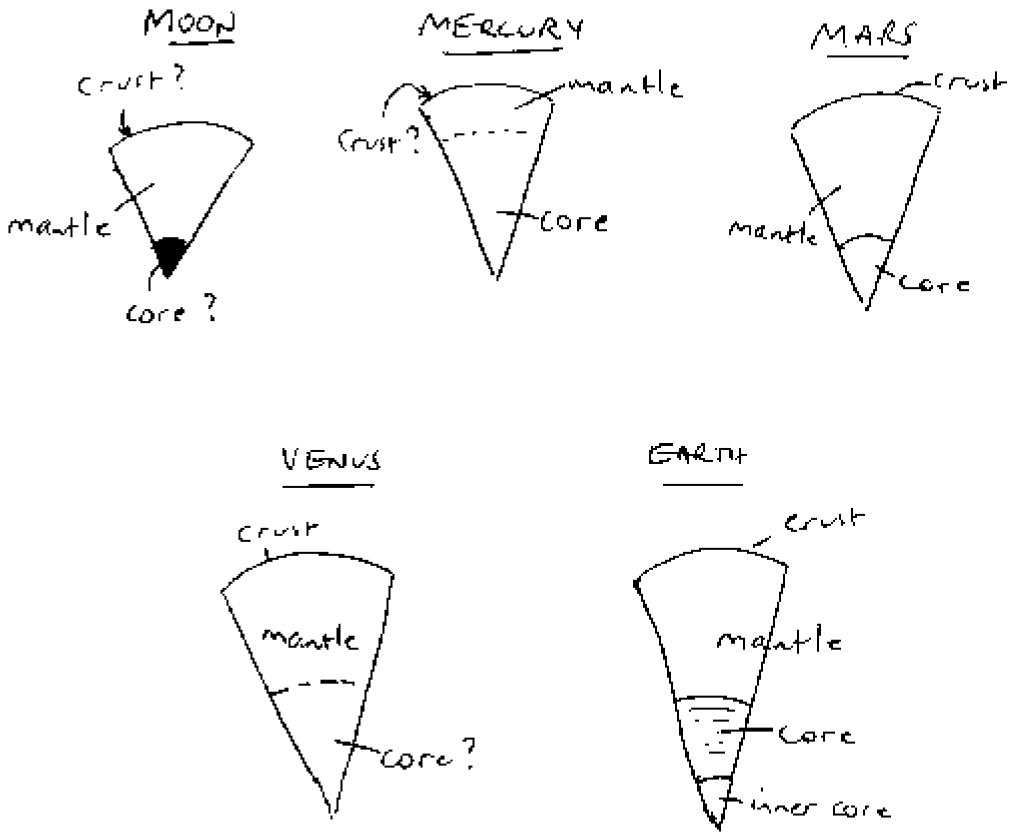
There is evidence of shrinkage distortion on its surface. Most of its volcanic activity seems to have been after the initial bombardment phase of the cratering: the surface is dominated by impacts but we see the volcanic origins between the craters. The surface is 80% cratered and 20% smooth plain, though we have to be careful about these figures and any conclusions we draw since it has only been half-mapped by Mariner 10. (Since the early Mariner photographs of Mars suggested it was lunar-like because we only had seen part of the surface, it is realised it is dangerous to draw conclusions about a whole planet when only a part of it has been imaged!) Some craters are worn. These cannot have weathered so it seems there was some lava flow after formation.

The upper limit on J_2 is very small, so the planet is close to hydrostatic equilibrium, and there is not enough information on "C" to make guesses about the interior. There is a small (but measured) intrinsic magnetic filed, about 0.00005 of Earth's. The "dipole" is inclined at 12 degrees inclined at 12 degrees to the spin axis. If it is a mystery why Venus has no magnetic field, we have the opposite problem with Mercury. It is believed a liquid interior is needed to generate a dipole field, but it seems unlikely Mercury could have a liquid interior. It could be that a primeval magnetic field was entrained as the material cooled through the Curie point, or it could be surface magnetisation. If some of the core is still molten, this could be due to a higher than expected proportion of radioactive elements.

There is, surprisingly, some evidence of ice at the poles (from radar reflections). It is not known if there is a crust, nor if there is a sharp core mantle division. There is probably some separation out between mantle and core but it is not known if this is due to differentiation or heterogeneous creation. The former of these would cause the loss of oxygen, but there is not enough information to know if this is true. [Lewis thinks the probability of differentiation is high.]

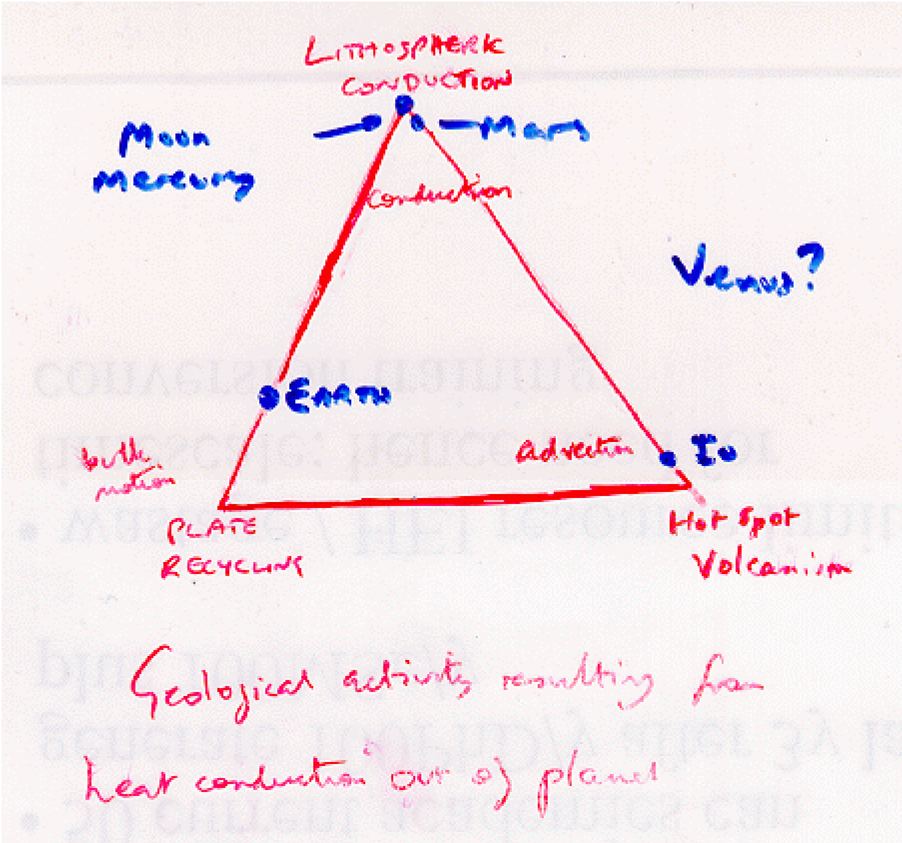
Comparison of Interiors of the terrestrial planets

We can show a rough comparison of what we believe the interiors of the terrestrial planets look like:



Heat Conduction from the terrestrial planets

We can show diagrammatically in what proportions the rocky planets lose heat from their interiors. They can do this by Conteriors. They can do this by Conduction, volcanism and plate recycling: thus geological activity is intimitely tied in with the heat transfer from the insides of planets. (We include Io as it is one] of the few good examples of "pure" volcanism) :



For more details see Beatty and Chaikin

Comparison of cratering on the terrestrial planets:

- Mercury - highly cratered, lunar-like
- Venus - cratered but lack of smallest craters and tendency to cluster medium-sized craters
- Earth - very little apparent cratering due to surface weathering and recycling
- Mars - lunar-like in places, but also areas where cartering is sparse and/or "filled-in" A ed-in" A