Did a mega-collision dry Venus's interior?

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Abstract

The limited relaxation of shapes of impact craters and high correlation between topography and gravity are some of the reasons that support the widely accepted view that the interior of Venus is dry compared to Earth. The fact that the atmospheric abundance of ^{40}Ar is only ~25% of the radiogenic gas produced inside Venus argues that Venus is not thoroughly degassed and its interior has not been dried over time. Therefore Venus must have lost its water very early in its history, before any significant ^{40}Ar was produced. Current ideas suggest that Venus did not suffer a major impact. Therefore one would not expect it to have been substantially molten. As a result degassing all its water would be difficult and losing all the water without leaving oxygen in the atmosphere would also be very difficult.

To overcome the above difficulties in explaining a dry Venus interior, a new hypothesis is proposed that Venus formed by a near head on collision of two large planetary embryos, as might be expected from favoured oligarchic planetary accretion. Such a collision would be sufficiently large to melt totally and briefly vaporise a significant proportion of both bodies. This would allow much of the released water to react rapidly with iron. Depending upon the reaction hydrogen is either expected to escape to space or enter the core. Oxygen would form FeO, most of which would enter the core, together with other iron reaction products. Most everything else not caught in the hydrodynamic escape driven by any hydrogen stream would be gravitationally retained by the final body. The model can therefore reconcile the ^{40}Ar data, a virtually oxygen free atmosphere and a dry interior. An appropriate large collision also provides an easy explanation for the retrograde rotation of Venus. The possible implications for inner core and magnetic field formation; and atmosphere evolution including effects on D/H, C, N and inert gases are also discussed. A simple test of this hypothesis is that, in contrast to the current Venus paradigm, little or no hydrated minerals should be found on the surface.

Keywords – Venus, water, impact, collision, oligarchic accretion, planet formation

1 Introduction

Venus is a sister planet to Earth. It is nearly the same size and its similar density suggests a very similar bulk composition. The major differences are therefore surprising. Venus has a surface temperature of 820 K, a surface pressure 70 times Earth, and an atmospheric composition dominated by carbon dioxide (oxygen < 0.1%), rather than nitrogen and oxygen (20%) of Earth. Venus's surface is covered by many large virtually pristine craters, and has no evidence for oceans, ridges, or the plate tectonics of Earth. These surface differences are commonly attributed to the fact that in contrast to Earth, Venus has a dry interior (Kaula, 1994; Kaula and Phillips, 1981; Stevenson, 2003b; Turcotte, 1996). While the Giant Impact Hypothesis is the leading paradigm for the formation of the Moon and Earth (Cameron and Ward, 1976, Hartmann and Davis, 1975), it is widely argued that Venus has not suffered a large impact since it does not have a satellite (Kaula, 1990). In contrast I propose that the drier Venus interior has arisen from a mega-collision.

1.1 Observations of water on Venus

We are confident that there is ~10^5 more water in the atmosphere/hydrosphere of Earth than the atmosphere of Venus (Prinn and Fegley, 1987). In contrast to the atmospheres there is more uncertainty regarding the water contents of the interiors, but again it is estimated that Venus's interior has at least one order of magnitude less water than Earth (Namiki, 1995, Zolotov, et al., 1997). The strong Venus rheology suggested by topography versus gravity correlations (Barnett, et al., 2002), the deformation of Devana Chasma (Nimmo and McKenzie, 1998) and large depth versus diameter of large craters which show limited relaxation (Grimm and Solomon, 1988) all support a dry interior. The large compensation depths (>100km depth) suggested by the Venusian topography gravity admittance also suggest strength at depth. The assumption is that the Earth rocks are weaker than even the hotter rocks on Venus (remember Venus surface temperature is much higher – and lack of plate tectonics would also lead to higher internal temperatures due to inefficient cooling) due to the presence of water, which is assumed to be absent on Venus (Mackwell, et al., 1998). It has also been argued that the lack of water is the reason that Venus does not have plate tectonics (Moresi and Solomatov, 1998), and also no low velocity zones (Richards, et al., 2001) or large continents (Turcotte, 1996). Both low velocity zones and continents are argued to reinforce plate tectonics.

1.2 How is Venus so dry?

For the atmosphere it has been argued that Venus lost its water to space following photo-dissociation of water in the upper atmosphere by Ultra-Violet (UV) radiation, followed by hydrodynamic escape of hydrogen (Hoyle, 1955, Ingersoll, 1969, Kasting and Pollack, 1983, Kasting, et al., 1984, Kasting and Toon, 1989). This process could be prevented by stratospheric cold trap preventing water reaching very high altitudes (Benz and Cameron, 1990, Holton and Gettelman, 2001, Ingersoll, 1969, Walker, 1990), especially at low water contents. For it to work oxygen also needs to be removed. Oxygen could be removed to space, but according to Chassefiere (1996) this is limited, especially if water is the source of the hydrogen while Kulikov et al. (2006) argue that it is possible. Oxygen could react with iron at the surface, but to oxidize Venus with one terrestrial ocean’s worth of oxygen would require the planet to be oxidised to a depth of 50km or more (Lecuyer, et al., 2000). While this would not be difficult to understand for a planet with plate tectonics it is harder to understand for Venus if it had a rigid and relatively immobile surface. While hydrodynamic escape of hydrogen is a plausible process (though we note caveats above) to dry the exosphere of Venus it does not address the water content of the interior.

One possibility to dry the interior of Venus is that it grew from planetesimals where very few of them were formed far enough from the Sun to incorporate significant amounts of volatile compounds such as water; i.e. the bulk of the Venus building blocks had condensed too close to the Sun, such that the higher temperatures prevented volatile compounds such as water condensing (Lewis and Prinn, 1984, Prinn and Fegley, 1987). The fact that other volatiles have similar or larger inventories on Venus than Earth, e.g. N and C, seems to argue against this idea (Donahue and Pollack, 1983). This is further reinforced by current ideas for planetary formation that require bodies to be built up by material from most of the terrestrial zone with only a weak history of the original condensation (Chambers, 2001) otherwise one would end up with many smaller planets (Chambers, 2004). While there could be a minor memory of the condensation history, it cannot explain the factor of $\sim 10^5$ difference that is observed between the atmosphere of Venus and the atmosphere/hydrosphere of Earth (Prinn and Fegley, 1987), and a factor of at least 3 (the rheology arguments above would probably require much higher differences) that is predicted for the interior (Michael, 1988, Rovetta, 1991).

A related alternative is that water was added to the Earth by late collisions with a few water rich embryos (Morbidelli, et al., 2000) which formed in the outer asteroid belt beyond 2.5 A.U.. While Canup and Pierazzo (2006) have started investigating the efficiency of this process, and the model has been extended to Mars (Lunine, et al., 2003) suggesting a drier Mars relative to Earth, the implications for Venus have not been evaluated in detail. Therefore it is not obvious that this process, at least by itself, would successfully explain the difference between Earth and Venus (and again the similar Earth and Venus inventories of C and N argue against it). The hypothesis that I present here could assume the mechanisms of this alternative, but rather than relating the different water contents of Venus and Earth to the variability of the water contents of the comparatively small number of large impacting bodies, it relates it to the details of the closing collisional history.

A third alternative is that both Venus and Earth have degassed their atmosphere over time, and in so doing got rid of the water from their interior; with Venus remaining dry, since unlike Earth it has been unable to recycle water because it has no subduction. Venus has outgassed about 25% of the ^{40}Ar that it has generated internally (Kaula, 1999, von Zahn, et al., 1983). Therefore Venus cannot have outgassed all its water by this means, over the timescale of ^{40}K half-life (1.3Gyr), else we would observe much more ^{40}Ar. So to repeat, while present ideas like hydrodynamic escape can possibly explain the differences in the water contents of Venus and Earth's exospheres they do not seem to easily explain the much drier interior.

2 Mega-Collision

[Figure 1 to be placed near here]

I suggest that Venus dried its interior as the result of a massive collision between two nearly equal sized embryos. In figure 1 I schematically outline the possible processes involved in such a mega-collision, guided by impact simulations. Figure 1a shows the start of the near head-on collision. As the collision proceeds increasing shocked volumes of the two bodies would change phase, also the water would be released from the hydrated minerals and could react with the free iron (figure 1b). Shocked material would also start to move outwards primarily in the plane perpendicular to the collision axis. It has been argued that at shock pressures of only 10GPa serpentine (hydrated mineral) would be totally dehydrated (Tyburczy, et al., 1991). There are at least two possible reactions between water and iron, $Fe + H_2O = FeO + H_2$; and non-stoichiometrically $6Fe + H_2O = 5FeH_x + FeO$ (where $x \sim 0.4$) (Badding, et al., 1991, Ohtani, et al., 2005, Yagi and Hishinuma, 1995). The resulting hydrogen would escape the body, while the iron oxide (and iron hydride) would form part of the solid body (figure 1c). Modelling of the Giant Moon impact suggests the production of iron vapour and that much of this vapour would rise to the surface providing plenty of opportunity for reaction with water (Canup, 2004). The opportunity for interaction would be increased in this proposed larger Venusian collision and by the rotation of the two cores through their mantles before they coalesce forming the core of the final body.

The carbonates would also devolatilise, but in contrast to hydrogen Venus would retain much of the denser carbon dioxide. The high temperatures would lead to a lot of vaporisation producing a very thick atmosphere, and the lighter vapour would preferentially extend in the perpendicular plane. Any water in this plane that can interact with the solar UV would dissociate and release hydrogen.

One is likely to produce also an iron and silicate vapour layers at the surface beneath an atmophilic layer (figure 1 d). These layers would all be very hot and turbulent allowing a lot of mixing and reacting (Benz and Cameron, 1990). The event would lead to a probably completely molten body (figure 1d), and therefore any remaining water in the interior could be efficiently outgassed. In the interior one would have a liquid silicate (magma ocean) layer, through which iron would descend as growing drops, collecting in the liquid core (figure 1 d-f), penetrating through solidified mantle as large iron diapirs (Stevenson, 1990) (figure 1 e). The opaque atmosphere would lead to a blanketing effect and would keep the magma ocean liquid for much longer than if it was covered by a thin or no atmosphere (figure 1f). Like current proposals for Earth, Venus is also likely to have received a ‘late veneer’ (Wood, et al., 2006).

The process would leave a carbon dioxide greenhouse atmosphere. Therefore the magma ocean would re-equilibrate with the atmosphere and the predicted internal water content of Venus would be related to the water content of this early atmosphere. The atmosphere would then undergo differentiation by hydrodynamic escape. This process has left its mark, especially in the isotopic ratios of gases, including noble gases (Donahue, et al., 1982, Kasting and Pollack, 1983, Pepin, 1991), and would start from a reduced water budget. This though would have only limited influence on the water content of the interior.

Since it is likely that a lot of vapour would have been produced in the impact, the turbulence and local mixing would allow the rapid reaction to ‘dry out’ the interior. A proposal of significant mixing due to turbulence, following the comparatively minor Moon forming collision, has been proposed to explain the surprising observation that Earth and Moon lie on the same oxygen isotope fractionation line. The reason why that observation is unexpected is that the oxygen isotopes of the parent bodies would be expected to be different, as observed in the very different array for Mars (Pahlevan and Stevenson, 2007). Further support for the possibility of extensive reaction is provided by the experiments that suggest that at even comparatively low impact pressures(20GPa) supercritical water is produced and it dissolves solid material easily, easing reactions (Furukawa, et al., 2007). This has been demonstrated most dramatically by shock wave experiments which produce complex products (peptides) from simple reactants (amino acids) even during the very short time-span of a laboratory shock wave experiment (Blank, et al., 2001). In the collision that I propose the iron vapour would rise towards the surface, while the iron liquid would descend towards the centre. While the details are poorly understood, one could imagine a very high energy and turbulent environment where the liquid droplets would initially be very small (maybe the estimate of maximum droplet size for iron droplets in a magma ocean by Stevenson (1990) would be relevant, ~ 1cm). The small scale of these iron droplets would allow rapid reaction, and they would re-equilibrate with the liquid silicate melt after only falling 60m (Stevenson, 1990). Similarly, the atmosphere will react rapidly with the underlying dense iron atmosphere. Therefore there should be many opportunities for water to react with iron, in comparison to the case of Earth where it is possible that a significant proportion of initial accreted water is held in the portion of the mantle that remains solid. As the collision died down one would imagine that the fine liquid droplets would coalesce and rain-out towards the centre. At some point the base of the mantle would solidify and any remaining iron in the magma ocean would pond at its base. Once enough iron has collected it would also make its way to the core by diapiric flow (taking the oxygen it has scavenged with it) (figure 1 f) (Stevenson, 1990). The same would be expected of any iron left in the solid phase. All of this material would be very hot. Some of the iron would possibly react with the liquid silicates producing solid-solution minerals with some iron end-member components such as fayalite, ferrosilite etc.

2.1 Oligarchic Growth

This hypothesis of a mega-collision fits with current ideas of planetary formation. Observations of disks around stars are now supporting theories of planetary formation from the collapse of proto-stellar nebular disks (Beichman, et al., 2005). These theories have advanced over the past 4 decades since the early work of Safronov (1969). The early work of people like Wetherill (1985) showed that in the hierarchical planetary formation process from dust through planetesimal and planetary embryos to planets one should expect a final stage of evolution of the terrestrial planets where large collisions would occur. Recently this has been refined to show that the final stage is one of oligarchic growth (Kokubo and Ida, 1998). In this case the run-away growth stops and the smaller planetary embryos start to catch up in size with the larger embryos. The planetary embryos will then tend to be around the same size. Therefore a collision between two large planetary embryos might be more likely than the final collision between two unequal bodies as proposed for the final major collision for Earth Moon system (Goldreich, et al., 2004). Therefore Earth Moon might be atypical, while Venus and Mercury might be more typical in having suffered a large collision. A collision between such bodies, would have deposited a large amount of energy, much more than that for the postulated Giant Impact for Moon formation.

2.2 Impact Energy

The minimum collision velocity (which assumes that the velocity at infinity of the bodies is zero) is the escape velocity. The escape velocity is

$$V_{esc} = \sqrt{(2G\,(m_1+m_2)/(R_1+R_2))} \qquad (1)$$

where $m_{1,2}$ are the masses and $R_{1,2}$ are the radii of the two bodies, and G is the gravitational constant. If the density (ρ) is the same in both bodies, then the escape velocity, can be written as

$$V_{esc}^2 = 2GM_T^{2/3}(4\pi\rho/3)^{1/3}/[\gamma^{1/3}+(1-\gamma)^{1/3}] \qquad (2)$$

where the total mass is M_T, and the ratio of the impactor to target mass is γ .

Specific impact energy per unit projectile mass, $E_{I,}$ is therefore

$$E_I = (4\pi\rho/3)^{1/3}GM_T^{2/3}/[\gamma^{1/3}+(1-\gamma)^{1/3}] \qquad (3)$$

Therefore the total energy in both impactor and target is proportional to $\gamma{*}E_I + (1-\gamma){*}E_T$ – where E_T is the specific impact energy per unit target mass.

Therefore, for a constant total mass one can show that the total collision energy peaks when both impactor and target have the same mass. A value of $\gamma = 0.5$ gives a total energy around twice the value for a $\gamma = 0.13$ (estimate for Giant Moon Impact) (Canup, 2004). Since models of Moon producing impacts produce large amounts of vapour; e.g. 23% in a typical simulation in Canup, (2004), we should therefore expect even higher levels of vapour and liquid formation in this mega-collision. Strictly it is likely that much of the volatile material is a fluid since it will be above the critical point. Such supercritical fluids are highly reactive, and of very low viscosity (Eckert, et al., 1996).

2.3 Collision angle – impact parameter

[Figure 2 to be placed near to here]

As I show in figure 2, based on the results from the modelling of a Mars collider with a proto-Earth, presented in figure 8a of Canup(2004), the orientation of collision plays a large role in the amount of material put into orbit. Since Venus does not have a satellite, I suggest that the collision would be close to head on (figure 1a). Canup (2004) shows (as seen in figure 2) that the mass in the debris disk drops dramatically as the collision becomes a head on impact; e.g. an impact parameter of 0.5 leads to a debris disk with ~0.1-0.2 of a Moon mass, in contrast to an impact parameter of around 0.7 which can lead to a debris disk with a mass similar to the Moon. From figure 2 we expect the mass of the debris disk to drop to virtually zero for a near head-on collision since the impactor does not have a chance to shear past the target.

The probability of a collision at an angle between α and $\alpha+d\alpha$ is given by $dP = \sin(\alpha) \cos(\alpha)\, d\alpha$ (Canup, 2004) . Therefore the probability for a collision between 0 and 30 degrees (i.e. close to head-on) is 25%; greater than the 13 % suggested probability for the Earth-Moon glancing collision (Canup, 2004).

2. 4 Why didn't the Moon forming collision dry the Earth?

The Moon forming collision was not as large a collision as suggested here for Venus, therefore there was less iron to fall through the mantle, and the mantle might not have been molten all the way to the core mantle boundary (Wood, et al., 2006), limiting the reaction. Also the head on collision hypothesised here for Venus formation would allow a more uniform deposition of energy in the colliding bodies, encouraging reactions throughout. In contrast the glancing Moon-Earth forming collision would lead to a more focussed deposition of impact energy and therefore more localised and limited extent of reactions. Also a liquid ocean, which existed on Earth, better survives the collision, in contrast to Venus where no water ocean was expected (Genda and Abe, 2005). We do note though that the Moon, which probably suffered the effects of the collision more extensively, is very dry.

3 Possible implications of a mega-impact

3.1 Atmospheres

Work of Genda and Abe (2005) suggests that less than 30% of the atmosphere would be blown away by such a mega-collision on Venus, partly because it is expected that the atmosphere of Venus is too hot (since it is closer to the Sun) to allow a liquid ocean to form. The Earth-Moon collision might have led to more atmosphere blow-off since the presence of an ocean helps with matching the impedance and transferring the energy to the atmosphere. An Earth-Moon collision though would remove virtually no ocean. Also the glancing nature of the Moon forming collision might allow increased blow-off of the atmosphere.

Since the Venus collision would also decompose carbonates, the carbon dioxide would rapidly be released to the atmosphere. This would further increase the blanketing effect, and prevent liquid water forming. With no ocean there is no means to dissolve the carbon dioxide and reform carbonates therefore we can expect nearly the whole inventory to be in the atmosphere. This inventory is similar to the whole carbon abundance estimated for all Earth reservoirs; atmosphere, hydrosphere, crust and mantle. Since it is a denser molecule than hydrogen or oxygen we should expect much less of it to escape via the hydrogen driven hydrodynamic escape.

The inert gases would not react and therefore would not suffer the fate of water on Venus. In contrast, as mentioned already, Earth collisions have been shown to better couple to the atmosphere due to the presence of an ocean (Genda and Abe, 2005). This allows more blow-off of atmosphere. Therefore that might be why Earth has a much lower abundance of inert gases compared to Venus. In such collisions Earth retains its water since it is mainly in the liquid ocean not the atmosphere. The inert gases, carbon and nitrogen would be the fractions in the solid or hydrosphere. Since the solubility of noble gases in water is very low, while it is high for carbon dioxide and nitrogen, this explains why Earth has maintained not only a lot of water, but also a large amount of nitrogen and carbon but less inert gases. There are also other explanations for the difference in inert gases between Earth and Venus (Owen, et al., 1992, Pepin, 2006) – we note that they need not be incompatible with the mega-collision hypothesis.

While early impacts could lead to fractionation (Tyburczy, et al., 2001), it is after the mega-collision that one would expect massive hydrodynamic escape, therefore at this stage Venus should lose many of its light atoms with little isotopic fractionation, possibly including water that had not been dissociated (Pepin, 1997). Once this process stopped the remaining water outgassed could be processed by the process suggested by Kasting and Toon (1989), leading to the observed D/H ratio (Donahue, et al., 1982, McElroy, et al., 1982), but from a more realistic initial inventory of water.

3.2 Venus rotation and obliquity

It has been shown that the final spin angular momentum of the planets is controlled by the last few major impacts (Agnor, et al., 1999). I would like to suggest that Venus resulted from a collision in which the two nearly equivalent sized proto-planets collided in such a way that the final spin was retrograde (see Figure 1a). If the Venus collision affected the spin as suggested (note though that the hypothesis does not require such an effect) this would add more energy to the impact as the rotational energy would be converted to thermal energy, (maybe as much as 10%). Such impacts are common in simulations (Chambers, 2001). While the fact that the rotation of Venus might be the result of a collision is not an original suggestion – the suggestion that it was so massive as to also dry Venus is. While the spin rate of Venus could be slowed by atmosphere and body tides, it is difficult for them to reverse the direction of the spin. Hence the simplest explanation of the retrograde spin is that Venus suffered a large impact. Laskar and Robutel(1993) though show that the obliquities of all terrestrial planets could be chaotic and therefore the retrograde rotation of Venus might not be primordial and it could have evolved from a slow prograde rotation; their analysis though does not require such an evolution. The scaling relationships of Canup and Ward (2001) suggests that such low final angular momentum in a collision will lead to low mass in a debris disk, and is therefore consistent with such a mega-collision not producing a satellite.

3.3 Core composition and magnetic field

As a result of the reaction I expect most of the iron oxide to end up in Venus's core, also possibly some iron hydride and other light elements. One speculative consequence of this might be a larger solidus depression making it even harder for Venus to form an inner core; though we note that for this to be significant the volumes of volatiles involved would probably have to be much greater than one terrestrial ocean's worth. The less efficient cooling of Venus's mantle (that one would expect with no plate tectonics) and lack of an inner core has been argued to be the reason for the absence of a magnetic field on Venus (Nimmo, 2002, Stevenson, 2003). Therefore a mega-collision might indirectly contribute to Venus's lack of magnetic field.

4 Discussion

To test this hypothesis, that a mega-collision has dried the interior of Venus, will require modelling, and that will require advances in the modelling of collisions. It will require including the possibility of reactions, and higher energies in impacts. There is only a poor understanding of how such a large collision would affect things in detail – e.g. how much carbonates and hydrated minerals would be decomposed; what would be the fate of the water, carbon, oxygen and hydrogen atoms; is the iron sufficiently dispersed in the collision to interact with the water etc? For example we can only confirm whether it is actually possible for Venus to retain around two orders of magnitude more inert gases than Earth while losing virtually all its water in a massive collision by advanced modelling.

We note that the proposal here is largely independent as to which mode water was delivered to Venus and Earth, be it interplanetary dust particles (Pavlov, et al., 1999), hydrated carbonaceous chondrites (Morbidelli, et al., 2000), or comets (Owen, et al., 1992).

The hypothesis is a way of explaining why Venus can have similar C and N budgets to Earth, but very different water contents. For the mechanism to work, it requires water on Venus to react with iron removing the hydrogen either to space or the core, and for the mechanism to be not as effective on Earth.

If all the water was lost from Venus by long term disassociation by extreme ultra-violet radiation in the stratosphere, then there would have been water to form hydrated minerals at the surface earlier in Venus's history. Since kinetic experiments have shown that they should have survived (Johnson and Fegley, 2003), a simple test to differentiate the two models would be to try and detect hydrated minerals on the surface of Venus.

5 Conclusion

I have pointed out that the current view of relatively quiescent formation of Venus is probably inconsistent with its much drier interior than Earth. In contrast I propose that Venus suffered a mega-collision during its formation. This allowed water to be removed by reaction with iron. Big collisions are not rare, but expected. This hypothesis would suggest that Earth was strange in having only 'small' collisions; while Venus and Mercury and possibly Mars suffered larger collisions in their evolution. The suggested result of these large collisions have included Mercury losing virtually all of its mantle (Benz, et al., 1988); and Venus becoming dry. Mars is a smaller body and would not have suffered as large a collision as Venus and hence it probably was able to retain more water in its interior.

The hypothesis presented has the potential to explain the dry interior together with the intermediate ^{40}Ar degassing, the D/H ratio, and the slow retrograde high obliquity rotation. Since such a collision leads to a dry mantle, it potentially also has many important implications for the tectonic evolution of the planets as suggested by others including ultimately explaining why Earth has plate tectonics and life and Venus does not. Quantitative predictions of this hypothesis will call for further advances in modelling and experiments on solar system evolution and large impacts (Canup, 2004, Chambers, 2004, Genda and Abe, 2003, Matsui and Abe, 1986); while one simple observational test to falsify this hypothesis is to find hydrated minerals on the surface of Venus.

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Figure Captions

Figure 1

This diagram presents a schematic of the stages of a massive collision. For further information see section 2, Mega-collision.

(a) Two hot, approximately equal-sized planetary embryos colliding close to head-on, possibly in a manner leading to the final body having a retrograde rotation.

(b) Shock waves from the collision propagating into and fluidising both bodies. The hot turbulent fluids encourage reactions, including reactions between iron and water producing hydrogen that can escape Venus.

(c) Collision continues, the two cores coalesce, and hydrodynamic escape gathers pace.

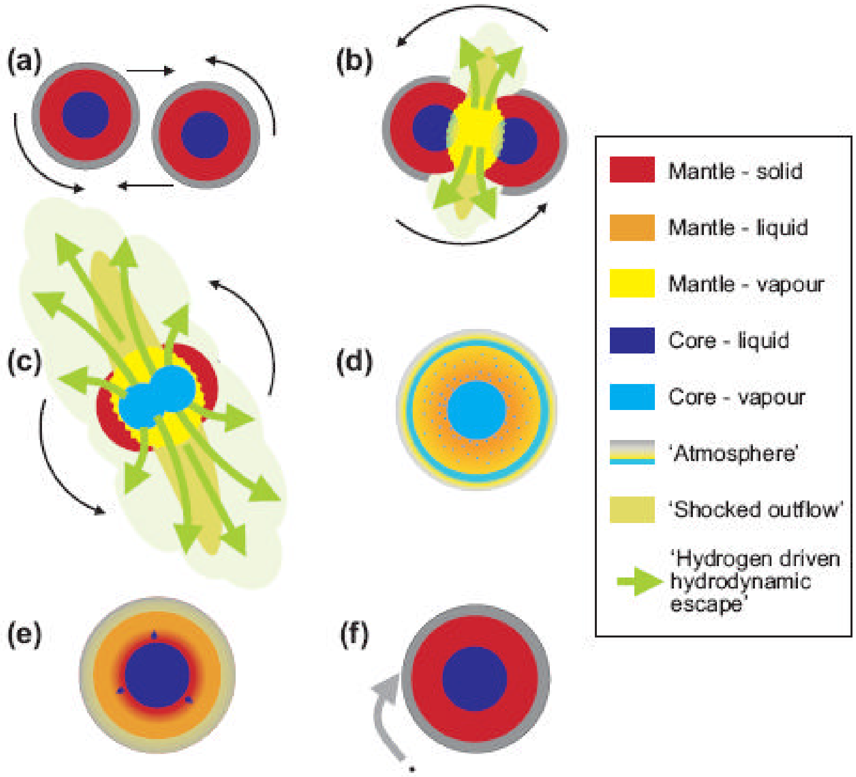
(d) Some hours to days later, the body recaptures most of its shocked outflow. It has a very hot molten core, a molten mantle with droplets of iron, a primitive crust, overlain by an iron vapour, silicate vapour and atmophilic atmospheres. Note there is no liquid ocean. There will be turbulent mixing and entrainment between the various atmospheric layers.

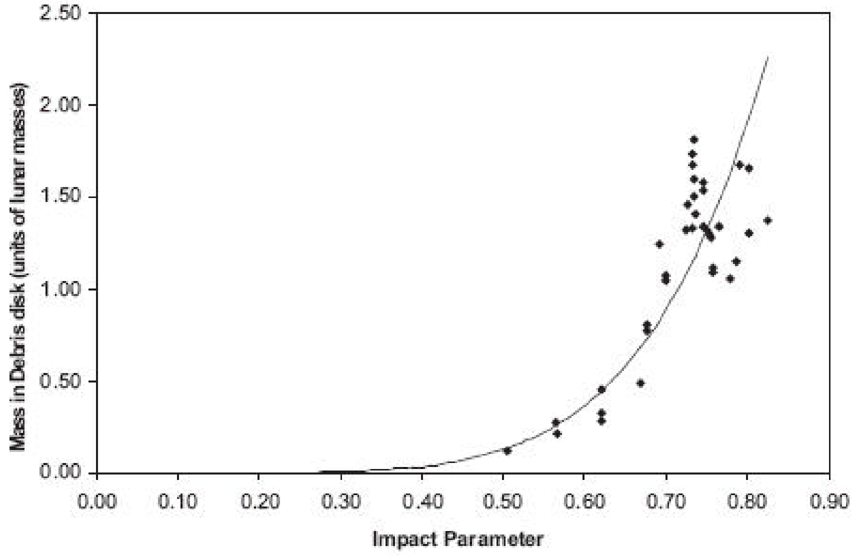
(e) Some thousands of years later, as the body cools further the mantle would start to solidify from its base, and remaining liquid iron would penetrate as diapirs through to the core.

(f) Millions of years later the final planet has a primarily solid mantle, a liquid core, and thick carbon dioxide atmosphere. There is no reason why Venus should not collect a 'late-veneer' if one was collected by Earth

Figure 2

This figure is adapted from Figure 8a of Canup (2004). It shows the amount of mass put into orbit in simulations of Earth-Moon forming Giant Impact simulations. I have fit a power law curve through the data to help guide the eye. It shows that at low impact parameter e.g. less than 0.4 (an impact angle of < 23 degrees), little mass would be put into orbit, and therefore that no satellite would be produced even by such a large collision. The impact parameter is the sine of the angle that the impact trajectory makes with the surface normal. An impact parameter of 0 is a perfectly head on collision, while an impact parameter equal to 1 describes a perfectly glancing collision.


(a)
(b)
(c)
(d)
(e)
(f)
Mantle - solid
Mantle - liquid
Mantle - vapour
Core - liquid
Core - vapour
'Atmosphere'
'Shocked outflow'
'Hydrogen driven hydrodynamic escape'


2.50
2.00
1.50
1.00
0.50
0.00
Mass in Debris disk (units of lunar masses)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
Impact Parameter