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Origin of the terrestrial planets and the moon

S R Taylor

Department of Nuclear Physics, Research School of Physical Sciences
Australian National University, Canberra, ACT 2000

Abstract

Our ideas about the origin and evolution of the solar system have advanced significantly as a result of the past 25 years of space exploration. Metal-sulfide-silicate partitioning seems to have been present in the early dust components of the solar nebula, prior to chondrule formation. The inner solar nebula was depleted in volatile elements by early solar activity. The early formation of the gas giant, Jupiter, affected the subsequent development of inner solar system and is responsible for the existence of the asteroid belt, and the small size of Mars. The Earth and the other terrestrial planets accreted in a gas-free environment, mostly from volatile-depleted planetesimals which were already differentiated into metallic cores and silicate mantles. The origin of the Moon by a single massive impact with a body larger than Mars explains the angular momentum, orbital characteristics and unique nature of the Earth-Moon system. The density and chemical differences between the Earth and Moon are accounted for by deriving the Moon from the mantle of the impactor.

The relation of the terrestrial planets to the solar system

The early history of the rocky terrestrial planets has to be placed in the broader perspective of the evolution of the solar system. They constitute such a tiny proportion of the original solar nebula that to a first approximation they could be ignored, except that we are standing on one of them. A basic question is whether the Earth and the other planets were formed by breakup of the gaseous solar nebula, or assembled "brick by brick" from smaller bodies. Were they formed in the nebula while the main gaseous and icy constituents were present, or had the hydrogen, helium, water, methane and ammonia, that constituted 99.5% of the primordial nebula, been dispersed before the formation of the inner planets? Why is Jupiter so large and what effect has it had on the rest of the system? Why is Mars so tiny, compared not only with the Earth, but to massive Jupiter? Why is there such a small amount of matter in the asteroid belt? Why is the Earth, and apparently Venus and Mars, depleted in volatile elements? Is this a local or more widespread phenonomen? Did the Earth accrete from a local zone in the nebula, or was there widespread mixing and homogenization in the early nebula? What is the relationship of the Moon to the Earth and what effect did the Moon-forming event have on the early Earth?

The solar nebula

The solar nebula initially separated as a small, slowly rotating, fragment of a molecular cloud. This allowed the formation of a single star surrounded by a rotating disk instead of the more common formation of a double star system, that constitute about 80% of all stars. Probably the disk was non-axisymmetric, which would allow both the inward flow of mass and the outward transfer of angular mometum (*e.g.* Boss 1988). Astrophysical evidence suggests lifetimes of a few million years before the nebula is dispersed. The composition of CI carbonaceous chondrites is very close to that of the solar photosphere for non-gaseous elements, and so is probably the best estimate available for the composition of the earliest condensed material from the solar nebula. Recent work has resolved the previous outstanding anomaly of distinctly different iron abundances: the new solar values now match the CI iron abundances (Holweger *et al.* 1990).

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Once the Sun has acquired about one third of its present mass, temperature and pressure conditions in the interior allowed H burning to begin. Observations on young stars suggest that the Sun underwent violent T Tauri and FU Orionis outbursts as it proceeded on its evolutionary path toward the main sequence. Strong stellar winds began to disperse the nebula, thus limiting the ultimate size of the Sun (*e.g.* Shu *et al.* 1987). Early violent solar activity may sweep away not only the H, He and other gaseous elements, but also ices and volatile elements not condensed or trapped in planetesimals large enough (metre-km size?) to remain in the inner nebula.

Loss of volatile Rb relative to refractory Sr and of volatile Pb relative to refractory U and Th appears to be widespread in the inner portions of the early nebula. Venus, Earth and Mars all appear to be depleted in volatile elements, as shown by their low K/U ratios, and by the U/Pb and Rb/Sr isotopic systematics in the case of the Earth. This depletion appears to be typical of the entire inner solar system out to perhaps 3 AU, at which distance more primitive asteroids begin to dominate the asteroid belt (Bell *et al.* 1989; Gaffey 1990). The age and initial Sr isotopic data from meteorites (Tilton 1988) record a single massive loss of volatile Rb relative to refactory Sr effectively at T_o, so that this was a nebular-wide event rather than being connected with isotopic evolution in individual parent bodies. The depletion of volatile elements must have occurred through physical processes (*e.g.* sweeping out of fine material by early solar winds) at relatively low temperatures, so that the nebula was cool at that stage.

Chondrules

Among the earliest events in the solar system was the formation of chondrules. These mm-size quenched silicate droplets form one component of chondritic meteorites. The other main constituent is the fine-grained matrix, complementary in composition to the chondrules, being notably enriched in Fe. Thus, the chondrules are not simply remelted matrix, and some segregation of the iron-rich matrix from the iron-poor chondrule precursor material must have occurred prior to the chondrule-forming events.

Formation of chondrules occurred in the nebula, rather than in any type of planetesimal or asteroidal environment (Taylor *et al.* 1983). They formed by a fast flash-melting type of process that did not change the composition of the parent material significantly (Lofgren & Russell, 1986; Radomdsky & Hewins, 1988; Hewins 1992). It is not possible to cool molten drops so rapidly in a hot nebula, so the process must have been highly localised in an overall cool environment (Wood 1987). Various scenarios exist to explain these observations of which the nebular flare model appears to be most consistent with observations (Levy & Araki, 1989). What was the nature of the chondrule precursor material? Metal, sulfide and silicate phases existed already in the early nebula, either as interstellar dust grains, or condensed from nebular gas (Grossman *et al.* 1988). How was the silicate dust melted preferentially, without involving the metal and sulfide phases to more than a minor extent? Perhaps silicate dust was separated from metal and sulfide, either by differential gravitational settling or magnetically in the case of the metal, or perhaps the silicates stuck together more efficiently (Scott *et al.* 1988).

The planetesimal hypothesis

A fundamental question about the origin of the Earth concerns the state of the precursor material prior to planet formation, and the mode of accretion of the planets. Did the terrestrial planets form directly from the dispersed dust and gas of the nebula or were they built up brick by brick from planetesimals? The concept that the Earth accreted cold from fine-grained dust and gas was long postulated by Urey (*e.g.* Urey 1952). The striking chemical heterogeneity of the planets and asteroids (Wasson 1985; Taylor 1988) argues against simple condensation models.

Several observations suggest that the inner planets are the end products of a hierarchical accretionary process that first produced a large number of planetesimals which were later accreted to form the larger planets (Safronov 1969; Wetherill 1986). What sort of evidence do we have for these now vanished objects? A major piece of evidence comes from the tilt or inclination of the planets to their axis of rotation. The largest impact is required to account for Uranus. Calculations show that a body the size of the Earth, crashing into that planet would be needed to tip it through 90^o (Benz & Cameron 1989). Smaller collisions are needed to account for the tilt of the other planets, but a few very large objects must have been responsible, since the impacts of many small bodies will average out (Benz *et al.* 1989).

The variable rotation rates of the planets may also be a consequence of giant impacts late in their accretional history. Venus, in contrast to the Earth, has a low obliquity, and is rotating slowly backwards. These properties may result from the accretion of Venus from many small bodies, and from the lack of a giant impact on that planet (Wood 1986; Wood, pers. comm.). It is also usually considered that the absence of a primitive terrestrial atmosphere is due to its early collisional removal. In this interpretation, Venus has retained a massive atmosphere due to the lack of large atmosphere-removing collisions with that planet. The high metal/silicate ratio of Mercury is best explained by stripping of much of the silicate mantle during a large collisional event, other hypotheses encountering many difficulties (Benz *et al.* 1988). Finally, the long-standing problem of the origin of the Moon is resolved by the impact of an already differentiated massive (0.14 earth mass) body with the Earth, the material making up the Moon being mostly (>80%) derived from the silicate mantle of the impactor (Benz *et al.* 1989).

How many objects were there and how big were they? Prior to the final sweep-up into the four terrestrial planets, Wetherill (1986) calculates that 100 objects of lunar mass, ten with masses exceeding that of Mercury, and several exceeding the mass of Mars should form. He further estimates that perhaps one-third of these objects, which would provide a total of 50-75% of present Earth mass, struck the Earth.

The formation of Jupiter

Early formation of Jupiter (318 Earth-masses) appears to be required for several reasons. The planet forms early enough to deplete the asteroid belt (which now contains only 5% of lunar mass) in material, and to be responsible for the small mass of Mars (0.11 Earth-mass). This low density region of the nebula seems unlikely to have been a primary feaure of the nebular disk even if the disk was non-axisymmetric. Jupiter must also form before the gaseous components of the nebula were dispersed. Other models such as the giant gaseous protoplanet hypothesis call for the formation of the planets by fragmentation of the primordial solar nebula. Jupiter should be the prime example of such a process. However, there are two principal objections. The moment of inertia data for Jupiter show that it possesses a central core of 15-20 earth masses. At the prevailing conditions in the center of Jupiter (40 mbars, 20000 K) rock and ice will be miscible with the gaseous components (Stevenson 1985). It will thus not be possible for a core to "rain-out" in the manner of a terrestrial planetary metallic core, where there are both significant density differences and metal-silicate immiscibility at the temperatures and pressures within the Earth (3.5 mbars, 5000 K; Stevenson 1985). Thus it is necessary to form a massive core first, which can then collect the gas by gravitational attraction.

A second objection is that Jupiter does not possess the solar bulk composition that would be expected if Jupiter were derived from a fragment of the primordial nebula; this gas giant has a (rock+ice)/(H+He) ratio about 10 times that of the Sun. Both these properties are readily explicable in terms of the planetesimal hypothesis.

However, it is first necessary to form a central core of 15-20 Earth masses, which can then collect the H and He envelope by gravitational attraction. How did such a large nucleus form so rapidly and so early at 5 AU from the Sun? A plausible scenario has been suggested by Lissauer (1987). As early strong solar winds associated with the T Tauri stage of stellar evolution sweep out the uncondensed components from the inner nebula, water ice will condense at about 5 AU at which location the nebular temperature falls below about 160 K. This condensation causes a local increase in particle density of the nebula at such a "snow line", which will also act as a "cold trap" for other components. Rapid accretion of a large ice and rock core can thus occur at this unique location, and act as a nucleus to collect a hydrogen and helium envelope. The low gas/(ice + rock) ratio in Jupiter implies that by the time that the core of Jupiter had grown large enough to collect a gaseous envelope, the gaseous nebula was already being dispersed, and that Jupiter simply ran out of material.

Accretion of the inner planets in a gas-free environment

Once Jupiter has formed, this massive planet dominates subsequent evolution of the solar system. After a few million years, the gas is gone and the ices and other volatiles have been swept away, so that the inner planets accreted from the left-over rocky debris. Depletion of material in the asteroid belt occurs both from accretion of material to Jupiter, and subsequent pumping up of eccentricities and inclinations of the asteroids remaining, so that the survivors have been unable to collect themselves into a planet. Others are tossed out of the system entirely. The asteroid belt appears to have existed from the earliest times. Thus the belt was not a very good quarry from which to obtain material for the inner planets. The accretion of Mars took place in a zone depleted in planetesimals from the same cause (early formation of Jupiter) and this region, at 1.5 AU again does not seem capable of supplying much material for Venus or the Earth.

Differentiation of precursor planetesimals

What was the history of the planetesimals prior to their incorporation into the inner planets? Some of the largest, the size of Mars, would have made respectable planets in their own right if fate had taken a different course. Were they already differentiated into silicate mantles and metallic cores before they came to a violent end as they were swept up into Earth or Venus?

Based on evidence from meteorites, even some relatively small planetesimals underwent internal differentiation into metallic cores and silicate mantles within a few million years of T_o (4570 my). The larger planetesimals had already gone through a melting episode, with silicate mantle and metallic core formation, before they were accreted by the inner planets (Gaffey 1990; Taylor & Norman 1990). Such bodies of course may have been broken up by collisions and reaccreted in differing proportions of metal and silicate fractions, so that much diversity of composition among the accreting bodies can be expected.

This question of heat supply for early planetesimal melting and metamorphism is essentially unresolved. Two principal mechanisms are currently discussed. If ^{26}Al ($t_{1/2}$ = 730 000 years) was present in the early solar system (Podosek & Swindle 1988), it could have constituted an important heat source. The second possibility is by inductive heating during the early intense T Tauri and FU Orionis stages of solar activity. Both of these mechanisms encounter difficulty and early planetesimal heating may be the result of processes not presently understood (J A Wood, pers. comm.).

A crucial question for the terrestrial planets is the width of the feeding zones from which they accumulated (Wetherill 1985). The limited data for Venus show similar K/U ratios to the Earth of about 10^3. This, coupled with the similar uncompressed density (about 4.0 g cm^{-3}) for the two planets, their similar size and their small separation of about 0.3 AU suggests that they accreted from a similar suite of planetesimals. Mars is less dense (uncompressed density 3.75 g cm^{-3}) and has a high obliquity and fast rotation rate, indicative of collisions with large objects. It is more volatile-rich than either Earth or Venus, having a K/U ratio of about 1.5 10^3. Thus Mars, about equidistant from the Earth and the main asteroid belt, appears to be distinct from both, suggesting that there was very little mixing within the nebula over distances greater than about 0.5 AU The survival of zoning in the asteroidal belt also points toward rather limited mixing. Other evidence includes the rarity of xenoliths of one class of meteorite in another. The great diversity in oxygen isotopic compositions (Thiemens 1988) including that of the chondrules (Grossman *et al.* 1988) is also strongly indicative of very limited mixing. In addition, the various classes of chondrites do not show simple chemical interrelationships which might indicate a heliocentric variation in composition. The general failure to identify specific classes of meteorites as building blocks for the terrestrial planets (*e.g.* Taylor, 1988) suggests that the inner planets accreted from rather narrow zones in the nebula, without incorporating much material from the location of the present asteroid belt.

The terrestrial Mg/Si ratio

The upper mantle of the Earth is depleted in Si and has an enhanced Mg/Si ratio relative to that of the primitive solar nebula. The bulk Mg/Si ratio of the Earth is uncertain since we do not know the Mg/Si ratio of the lower mantle. The debate over this question is unresolved (*e.g.* Anderson 1989). Recent suggestions that mantle plumes, responsible for hot-spot volcanism, are derived from the core-mantle boundary (Griffiths & Campbell 1991; Sleep 1992), imply that the whole mantle is involved and that there is significant mixing between upper and lower mantle. If the lower mantle of the Earth has the same Mg/Si ratio as the upper mantle, then the implications for the accretion of the Earth are considerable. In this event, the Earth accreted from a set of planetesimals with non-CI Mg/Si ratios. The variation in Mg/Si in chondrites covers such a wide range that the existence of planetesimals with higher Mg/Si ratios seems possible. This would imply a very large reservoir of planetesimals at about one AU with Mg/Si ratios significantly higher than solar.

Core-mantle relationships

The highly siderophile elements would have been efficiently extracted into the metal core under equilibrium conditions. However the present upper mantle was apparently never in equilibrium with the core, for the abundances of Re, Au, Ni, Co and the platinum group elements (PGE= Ru, Rh, Pd, Os, Ir, Pt), although low, are higher than predicted (Arculus & Delano 1981; Delano 1986; Newsom & Palme 1984; Newsom 1986). Late accretion of CI planetesimals rich in PGE is a common explanation for their over-abundance in the upper mantle. The addition of the metallic core of the impactor responsible, in the single impact hypothesis, for the origin of the Moon (Benz *et al.* 1989) is another possible source of material. A cometary influx might be an equally viable source, although the high impact velocities of comets derived from the outer solar system may cause removal rather than addition of material.

The 'predestination' scenario (Taylor 1983; Taylor & Norman 1985; Murthy & Karato in press) in which the terrestrial planets accrete from planetesimals which were already mostly differentiated into metallic, silicate and sulfide phases implies little further reaction between metal and silicate once these bodies accreted to the Earth. In this scenario the core mantle relationships were mostly established at low, and not high pressures.

A further consequence may be noted. The metallic core of the Earth contains about 10% of a light element. The two current contenders are oxygen and sulfur. Although meteorites are not a perfect analogue for the terrestrial precursor planetesimals, they do tell us that elemental and mineralogical fractionation was endemic in the early nebula. If silicate, sulfide and metal phases, formed under low-pressure equilibrium conditions, were already present in the accreting planetesimals, separation of these phases may occur concomitantly with accretion and thus there may be little high-pressure equilibration between core and mantle in the Earth. Thus it seems unlikely that oxygen entered the core, since this requires megabar pressures. Sulfur then becomes the most viable candidate for the light element in the earth's core. Since metal-sulfide-silicate equilibria was accomplished predominantly at low pressures in precursor planetesimals, troilite will be the main source of sulfur.

Late Veneers

A number of possible effects of late additions to the Earth have been proposed. Thus comets are often invoked as a source of water (*e.g.* Chyba 1987). A cometary source may also account for the difference in the atmospheric abundances of the rare gases in the Earth, Venus and Mars (Owen *et al.* 1992). This concept is attractive since, in the scenario developed here, the inner solar system is depleted in water and other volatiles. Furthermore, the terrestrial water budget, although uncertain, probably constitutes less than 500 ppm of the mass of the Earth (Bell & Rossman 1992; Thompson 1992). This is less than $^{1}/_{1000}$ of the water budget in the primitive nebula and could readily be suppplied by a few large comets. Such stochastic processes also rather conveniently account for the differences among the terrestrial planets: the vexed question of the missing water on Venus is simplified if that planet never had any to begin with. Comets, however, may be a fickle source of atmospheres and hydrospheres, since they impact with relatively high velocities and thus may remove as much material as they contribute (*e.g.* Melosh & Vickery 1989). There are various other unresolved problems with the concept of late veneers. The Moon shows no evidence of such events and the Moon remains "bone-dry".

Mercury

A large impact is probably responsible for the strange fact that Mercury has such a small rocky mantle and such a large iron core, and an inclined orbit so close to the sun. Two explanations are current. The first proposes that that the silicate was boiled away in some early high temperature event, connected with early solar activity (the surface temperature on the present sunlit side of Mercury is 425 ˚C, and hot enough to melt lead). However, extremely high temperatures of several thousand degrees are required to boil off the rocky mantle. The alternative explanation, is that Mercury was struck by a body about $^{1}/_{6}$ of its mass at a late stage in its accretion. The collision fragmented the planet with most of the silicate lost to space but the iron core surviving to reaccrete with a depleted silicate mantle (Benz *et al.* 1988). If Mercury has a plagioclase-rich crust analogous to the lunar highlands, then it is likely to be depleted in the more volatile elements, since flotation of such a crust in a magma ocean requires a water content less than 0.1% (Walker & Hays 1977). Attempts to secure a K/U ratio for Mercury, which would shed some light on these interesting problems, should be accorded a high priority.

The origin of the Moon

The broad aspects of lunar evolution are well understood. The moon was partially or wholly melted at, or shortly after, accretion. This vast mass of molten silicate has been termed the "magma ocean" and a high temperature and rapid mode of origin for the moon is required to account for it. The crystallisation of the magma ocean is understood in principle (*e.g.* Taylor 1982; Warren 1985). Feldspar was an early phase to crystallise. It floated, due to the low density of the feldspar crystals and the anhydrous nature of the silicate melt, and formed a thick feldspathic crust by 4440 my. Convection during cooling may have swept "rockbergs" of feldspar together, accounting for the variations in crustal thickness. A small lunar iron core about 2-5% by volume formed in the centre. This sequestered the siderophile elements. The lunar mantle was fully crystallised by about 4400 my, and resulted in a zoned silicate mineralogy, from which the mare basalts were derived much later by partial melting. This cumulate hypothesis for the source region of mare basalts is well established (*e.g.* Taylor & Jakes 1974; Fujimaki & Tatsumoto 1984). As the silicate minerals crystallised, those trace elements which were excluded from their crystal lattices were concentrated in the residual melt. The final stage of magma ocean evolution was the intrusion of this residual liquid into the feldspathic highland crust. The fluid was enriched in elements such as Th, U, Zr, Hf, Nb, K, REE, P (from which the acronym KREEP has been coined) and is responsible for the extraordinary near surface abundance of elements such as K, U, Th, and REE, which may be concentrated by factors of several hundred relative to bulk moon or primitive nebula values. It pervaded the crust, with which it was intimately mixed by the continuing meteoritic bombardment. The final event in crustal evolution was the intrusion of an Mg and KREEP-rich suite of rocks, produced perhaps by sub-crustal melting induced by the impacts of giant planetesimals. Bulk moon models which contain more than 5% Al_2O_3 provide the best match to the seismic velocity profile, implying that the moon is enriched in refractory elements relative both to the Earth and to primitive solar nebula levels. This conclusion has been confirmed by data from the Clementine mission (Lucey *et al.* 1995)

Hypotheses of lunar origin

The major models for the origin of the Moon can be grouped into five separate categories, which include;

(a) capture from an independent orbit;

(b) fission from a rapidly rotating Earth;

(c) formation as a double planet;

(d) disintegration of incoming planetesimals; and

(e) Earth impact by a Mars-sized planetesimal.

All fail to account for the unique nature of the Earth-moon system except the last. This process accounts for the high angular momentum ($3.45\ 10^{41}$ rad g cm^2 sec^{-1}) of the Earth-Moon system and the non-equatorial lunar orbit as well as providing extreme temperature conditions which can produce an initially molten Moon and the bone-dry features of lunar geochemistry. Computer simulations of the giant impact hypothesis under conditions that form a lunar mass depleted in metallic iron in terrestrial orbit clearly indicate that it is mostly the material from the silicate mantle of the impactor that finishes up in the Moon (*e.g.* Cameron & Benz 1991). This conclusion is reinforced by the geochemical problem of the failure to match Earth mantle and lunar compositions for a number of crucial elements (*e.g.* Taylor 1986a,b; Newsom & Taylor 1989).

The similarity in oxygen isotopes between the Earth and Moon indicate derivation of both the Earth and the impactor from the same region of the nebula, thus excluding models that derive the impactor from the outer reaches of the solar system. The similarity in $^{53}Cr/^{52}Cr$ ratios (^{53}Cr is derived in part from short-lived ^{53}Mn) between the Earth and the Moon and their contrast with higher meteoritic values (Lugmair & MacIsaac 1995) carries the same implication of derivation of lunar material from around 1 AU. A third constraint is the relatively low collision velocity (Benz *et al.* 1989; Cameron & Benz 1991) required to produce a Moon-sized body, which again restricts the impactor to be a nearby object. If the material in the Moon is derived from the impactor, then that body had a lower Rb/Cs ratio than the Earth. The primitive lunar initial $^{87}Sr/^{86}Sr$ ratios indicate that the impactor must have been depleted in Rb relative to Sr very close to To.

Current models assume that core-mantle separation occurred in both the impactor and the Earth before impact, to account for the lunar siderophile element abundances and the lunar depletion in iron (13% FeO) relative to primordial solar nebula volatile-free abundance levels (as shown by the CI meteorites) of 36%. The abundance of FeO in the mantle of the impactor must however have been greater than that of the terrestrial mantle (8% FeO), since the bulk Moon contains a much higher abundance. Mars, in contrast, has a mantle FeO content of 18%.

Effects on the Earth of the Moon-forming impact

The important consequence of the single giant impact event for the Earth was that the energies involved are sufficient to melt the Earth. However, such melting is probably inevitable if the Earth was accreted from a hierarchical suite of planetesimals, regardless of whether the Moon-forming event occurred. Any primitive atmosphere is removed, which probably accounts for the very much lower ^{36}Ar content (by about two orders of magnitude) of the terrestrial atmosphere compared with that of Venus.

The lack of geochemical evidence for early differentiation of the Earth (*e.g.* McFarlane & Drake 1990) analogous to that shown by small-scale terrestrial layered intrusions (*e.g.* Skaergaard, Stillwater) or by the Moon may be due to the scale of the event. Thus a molten terrestrial mantle may be turbulent, and crystals may not have had the opportunity to settle, thus precluding large-scale fractionation (Tonks & Melosh, 1990)

In addition to the accretion of the impactor's core, about 10% of the mass of the Earth's mantle is added from the impactor's mantle. The models of Benz *et al.* (1989) indicate that most of the metal core ends up in the Earth, with the metal penetrating the mantle and ending up wrapped about the Earth's core. Such an event would not disturb siderophile abundance patterns already present in the Earth's mantle. However, a significant amount of material from the impactor's core, enriched in siderophile elements, will probably be vaporized and redistributed into the mantle.

Conclusions

1. Depletion of volatile elements in the inner nebula occurred effectively at T_o before the chondrules were formed and affected the solar nebula out to about 3 AU The probable mechanism was dispersal of uncondensed volatiles by early strong stellar winds during the T Tauri stage of solar evolution.
2. Jupiter formed early before the gas component in the nebula was totally depleted.
3. Accretion of the Earth, inner planets and the asteroid belt took place in a gas-free environment in the inner solar system following the formation of Jupiter.
4. The terrestrial planets were built from precursor planetesimals that had survived the clearing of the inner solar nebula. The larger ones had already formed metallic cores and silicate mantles and had already experienced at least one episode of melting and differentiation.
5. Because this metal-sulfide-silicate fractionation occurred largely at low pressures, the geochemistry of the core and mantle may instead be dominated by the low-pressure equilibria established in the precursor planetesimals. Sulfur becomes a viable candidate for the light element in the core
6. Only limited mixing occurred in the inner nebula during planetary formation, with accretionary zones perhaps 0.3 AU wide. Very little material from the asteroid belt was incorporated in the Earth.
7. The Moon formed as the result of a single giant impact of a Mars-sized body with the Earth. Most of the

material in the Moon came from the mantle of the impactor.

8. The Earth was melted either as a result of the Moon-forming event, or as a consequence of its accretion from a hierarchical sequence of planetesimals.

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