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The origin of the Earth

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It is not possible to consider the formation of the Earth in isolation without reference to the formation of the rest of the solar system. A brief account is given of the current scientific consensus on that topic, explaining the origin of an inner solar system rocky planet depleted in most of the gaseous and icy components of the original solar nebula. Volatile element depletion occurred at a very early stage in the nebula, and was probably responsible for the formation of Jupiter before that of the inner planets. The Earth formed subsequently from accumulation of a hierarchy of planetesimals. Evidence of these remains in the ancient cratered surfaces and the obliquities (tilts) of most planets. Earth melting occurred during this process, as well as from the giant Moon-forming impact. The strange density and chemistry of the Moon are consistent with an origin from the mantle of the impactor. Core-mantle separation on the Earth was coeval with accretion. Some speculations are given on the origin of the hydrosphere.

The relation of the Earth to the solar system

Although the Earth is unique, it is not possible to discuss the origin of the Earth separately from that of the other 'terrestrial' planets, or from that of the entire solar system. The presence of its unique satellite, the Moon, must also be accounted for. The planets are usually divided into three major groups: the small terrestrial planets (Mercury, Venus, Earth, Mars), the gas giants Jupiter and Saturn, and the smaller ice giants Uranus and Neptune. Pluto is only called a planet by courtesy. It is one of the larger icy bodies from the Kuiper Belt, is only 20% of the mass of the Moon, and is similar to Neptune's satellite, Triton.

The inner solar system with its small rocky planets is distinct from the region of the giant planets that dominate the outer reaches of the system. A basic reason for this division was the depletion of volatile elements and loss of gaseous elements in the inner nebula. This was probably associated with violent solar activity in the earliest stages of nebular evolution. Jupiter and Saturn formed while the gas was still present and at a significantly earlier stage than the inner planets. The terrestrial planets accreted later from left-over planetesimals after the gaseous components of the nebula had been dissipated.

The solar nebula

The planets all rotate around the sun anticlockwise when viewed from above and all lie close to the Earth–Sun or ecliptic plane. This pattern is due to the formation of the Sun and planets from a spinning disk of dust and gas, the solar nebula, a concept that was formulated by the French scientist Pierre-Simon, Marquis de Laplace (1749–1827), about 200 years ago.

The solar system began to form about 4570 million years ago from the solar nebula. This is the age of the refractory inclusions in some meteorites, which appear to be the oldest objects that formed in the nebula. The disk of dust and gas had become separated as a fragment from a larger molecular cloud in a spiral arm of the galaxy about 12–15 billion years after the Big Bang.

Following its separation as a fragment of a molecular cloud, the primitive solar nebula consisted mainly (98%) of gas (H and He) with about 2% of heavier elements, which are divided into 'ices' (water, ammonia, methane, about 1.5%) and 'rock' (about 0.5%) (Levy & Lunine 1993). We are well informed about the composition, for the non-gaseous elements, of the primordial solar nebula. This is because of the close correspondence between the abundances of the non-gaseous chemical elements in the solar photosphere, and in the CI chondritic meteorites.

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Volatile element depletion in the inner nebula and the formation of Jupiter

The inner solar system is depleted not only in gas, but also in elements that are volatile below about 1200K (Taylor 1992). This depletion is well illustrated by the abundance of potassium (a moderately volatile element) compared with that of uranium (a refractory element). Both these elements are gamma-ray emitters, which means that geochemical measurements can be made for Venus, Mars and the Moon as well as the Earth (Fig. 1). The Venusian data come from gamma-ray measurements made by the Russian Venera and Vega landers, the Martian data from the meteorites from that planet that have landed on Earth.

Potassium and uranium are distinctly different in chemical properties, ionic radius and valency. However, both elements are concentrated in residual melts during crystallisation of

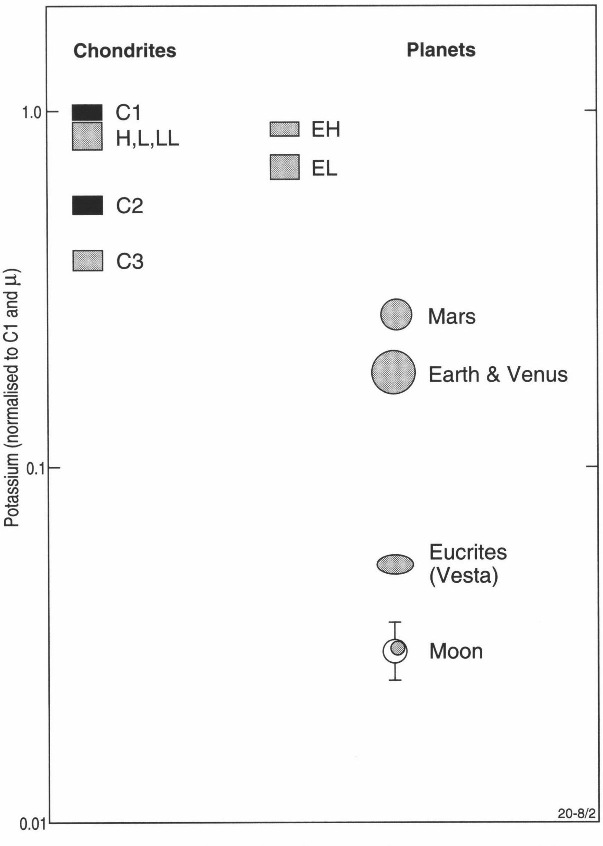

Figure 1. Depletion of volatile elements, here represented by potassium, relative to refractory elements (e.g. uranium) is widespread in the inner solar system. Most classes of meteorites have higher K/U ratios than the planets. The Moon is more highly depleted in K and other volatile elements than the terrestrial planets (after Humayun & Clayton, 1995).

basaltic silicate melts, since they are both excluded from the common rock-forming minerals in basalts (i.e. they are 'incompatible' elements). Thus they tend to preserve their bulk planetary ratios during planetary differentiation. It has occasionally been suggested that potassium could behave as a metal at high pressures and so be buried in the metallic planetary cores. However, although potassium is depleted on Mars, the pressure at the centre of Mars (r=3390 km; 400 kb) is insufficient to allow potassium to enter a Martian core. In addition to potassium, many other volatile elements are also depleted in the Earth relative to primitive nebular abundances. Most of these elements have chemical properties which make it unlikely that they would enter into metallic phases.

Perhaps potassium, which is a moderately volatile element, could have been boiled off during a high temperature stage of planetary accretion. However, it turns out that elements of the atomic weight of potassium cannot be lost from the terrestrial planets once these bodies have reached their present size. The K/U ratio should vary with planetary size, if they were boiled off in some manner during accretion. This is not observed. Neither are there any signs of isotopic fractionation that would occur in such a process (Humayun & Clayton 1995).

The Rb/Sr isotopic systematics show that the Earth is depleted in volatile rubidium relative to refractory strontium. Rubidium has closely similar properties to potassium, so that it is unlikely that either element is present in the mantle in its primordial solar nebular abundance. It is a clear conclusion that, in common with the other volatile elements, rubidium was depleted in the precursor material from which the Earth accreted.

The time of volatile depletion in the inner nebula is given by the ages of the meteorites. The Pb-U and Rb-Sr ages give the time of separation and depletion of volatile lead and rubidium relative to refractory uranium and strontium from the primordial solar nebula values. This depletion in volatile elements occurred before 4566 m.y. The most likely explanation is that when the growing sun reached critical mass and thermonuclear burning began, violent T Tauri and FU Orionis activity swept out the gas and uncondensed elements from the inner nebula. Metre-sized planetesimals survived and these subsequently accreted into the terrestrial planets. Water condensed as ice in the nebula at 160K at what is termed a 'snow line' at 4–5 A.U. (Astronomical Unit, the mean distance between the Earth and the Sun, 1.496 10^8 km) (Taylor 1992; Levy & Lunine 1993).

A massive core of about 15 Earth masses was able to form within about a million years due to this pile-up of water ice at 5 A.U. This core was sufficiently massive to trap hydrogen and helium by gravitational attraction and so Jupiter grew rapidly. The early formation of Jupiter had profound consequences. It depleted the asteroid belt and pumped up the orbital inclinations and eccentricities of the remaining asteroids so that they were unable to collect themselves into a planet The region where Mars would later accumulate was starved. Mars is only 1/3000 as massive as Jupiter. Within the inner nebula, only bodies large enough (metre size) to survive the early intense heating episodes from the early Sun were left.

The accretion of the Earth from planetesimals

Earlier views that the Earth and the inner planets accreted from fine dust have been discarded. Such a process of planetary formation would lead either to planets of uniform or smoothly varying composition. Obliquities would be expected to be zero and rotation rates likewise uniform and possibly very low or zero.

The former presence of a hierarchy of planetesimals is indicated by several lines of evidence. Direct evidence for the

Figure 2. Mare Orientale, 900 km in diameter, is a type example of a multi-ring basin formed by the impact of a planetesimal or asteroid perhaps 100–200 km in diameter. The concentric rings of mountains were formed within a few minutes, 3800 million years ago (courtesy NASA Lunar Orbiter IV 187M).

previous existence of bodies up to 100 km in diameter comes from the observation that ancient surfaces on planets and satellites are saturated with craters. From Mercury, close to the Sun, out to the satellites of Uranus, a massive bombardment struck planets and satellites. The lunar surface is the classic example. Craters, from micron-sized pits due to impact of tiny grains on lunar samples, up to giant ringed basins over 1000 km in diameter, are present (Fig. 2). The planetesimals ranged in size from a few metres up to Mars-sized objects. The asteroids are our best current examples (Fig. 3) (Binzel et al. 1990).

Were there larger intermediate-sized bodies (Moon–Mercury–Mars size) in the hierarchy of objects which accreted to form the terrestrial planets? The major piece of evidence for the presence in the early solar nebula of very large objects (of lunar, Mars and Earth-sized masses) comes from the obliquity or inclination of the planets to their axis of rotation. A body the size of the Earth crashing into the planet would be needed to tip Uranus through 90°. Although smaller collisions are required to account for the tilt of the other planets, objects at least as large as Mars (1/10 Earth mass) must have been responsible, since the impacts of a multitude of smaller (Phobos-size) bodies will average out.

How many of these very large objects were there? Computer simulations of the accretion process in the inner solar system show that about 100 moon-size bodies, 10 Mercury-size and 3 to 5 Mars-size bodies would have formed the final population of planetesimals existing just before the final sweep-up into

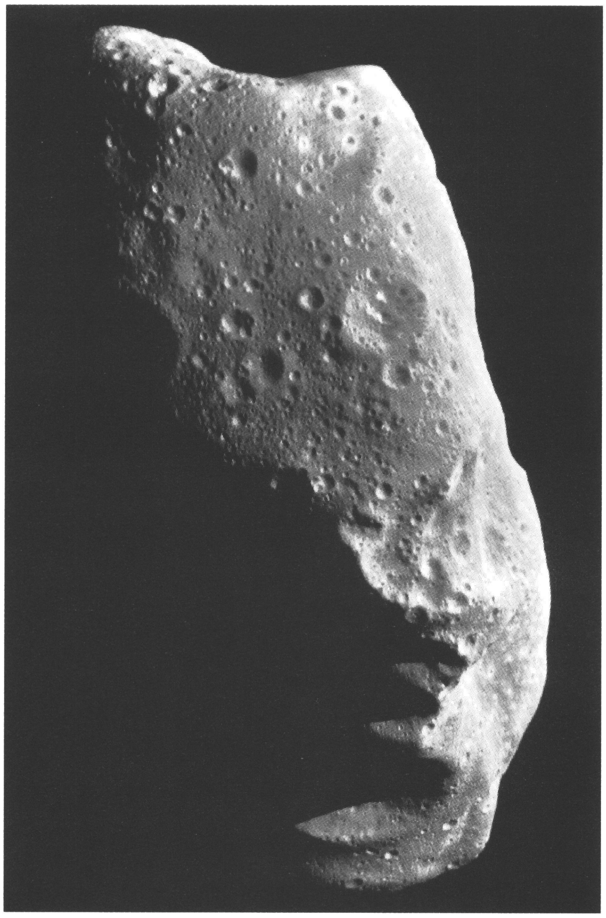

Figure 3. An analogue for a small planetesimal. The S-class asteroid 243 Ida, 56 × 24 × 21 km. Its density of 2.6 ± 0.5 g/cm^3 is consistent with a bulk chondritic composition and a porous structure.

Venus and the Earth. Mars, only 1/10 of the mass of Earth, and Mercury, only about 1/20 Earth mass, are survivors of this population.

A large impact is probably responsible for the strange facts that Mercury has such a high density and a small rocky mantle. The current view of Mercury is that a body about 1/6 of its mass struck Mercury at a late stage in the accretion of the planet. The collision disrupted the planet: most of the mantle silicate was lost to space, but the iron core clumped together with a smaller silicate mantle. The origin of the Moon also involves a collision of an object larger than Mars with the Earth, resulting this time in the production of a low density satellite. From this discussion, it is apparent that there is ample evidence for the existence of large precursor bodies or planetesimals in the early solar system.

The Earth and the other inner planets formed through the accretion of those planetesimals which were left in the inner nebula after the gas was swept away. At an early stage in solar nebular evolution, the dust in the rotating disk of the solar nebula began to clump together, beginning with grains and proceeding through metre-sized lumps to objects of kilometre size, finally reaching dimensions of hundreds to thousands of kilometres during the final stage before planetary accretion. The larger planetesimals were probably melted early in solar system history and differentiated into metallic cores and silicate mantles. Based on evidence from meteorites, even some relatively small planetesimals underwent internal differentiation into metallic cores and silicate mantles quite early in their history. The larger planetesimals almost certainly had already gone through at least one intraplanetary melting episode, with core formation occurring before they were accreted by the inner planets. Such bodies 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 (e.g. Newsom & Jones 1990). Possibly, some undifferentiated planetesimals were added late in the accretionary sequence. Such a 'late veneer' could account for the excess siderophile elements in the upper mantle, as well as adding water.

The terrestrial planets collected somewhat differing populations of planetesimals and differ in composition among themselves. The absence of a planet in the asteroid belt, in which over 4000 small bodies have been labelled, is due to the influence of massive Jupiter, which swept up, or ejected many of the bodies. As noted earlier, the total mass of the many small objects in the belt is less than 5% of the mass of the Moon. The small size of Mars is due to a similar cause: starvation caused by massive Jupiter, which formed earlier and depleted the neighbourhood.

Over 120 asteroids (the Apollos) perturbed from the asteroid belt are in Earth-crossing or Earth-approaching orbits. Once in these orbits, they have lifetimes of only about 100 m.y. Somewhere between 100 and 1000 tons of meteoritic material, mainly as dust, falls on the Earth each day. Every few million years an asteroid large enough to form a 20 km diameter crater hits the Earth. The extinction of 70% of species, including all the dinosaurs at the end of the Cretaceous Period, 65 million years ago, was most probably due to the impact of an asteroid some 10 km in diameter. The evidence for the collision includes a worldwide 'spike' in iridium (rare in the Earth's crust, but more abundant in meteorites), quartz grains shocked by pressures of hundreds of kilobars, and soot from massive fires, at the exact Cretaceous–Tertiary boundary. No internal single geological process can account for these facts.

Although the inner planets are chondritic in a broad sense, it does not appear possible to construct the Earth and the other terrestrial planets out of the building blocks supplied by the currently sampled population of meteorites. There are many differences in detail between the present population of meteorites and the compositions of the terrestrial planets. These include volatile/refractory element ratios such as K/U, oxygen isotopes, noble gases, and density. These rule out any of the known meteorite classes as potential candidates for the source material for the inner planets. If they are providing us with an adequate sample of the inner asteroid belt, then there were substantial differences between that area and the zone sunwards of about 2 A.U. The most significant difference appears to have been a generally greater depletion of the volatile elements in that region in which the terrestrial planets accumulated (Wasson 1985; Kerridge & Matthews 1988). As always, there are exceptions to this tidy scheme. Thus the eucrites derived from the asteroid Vesta are also depleted in volatile elements.

The asteroid belt was depleted by the early formation of Jupiter, so that very little material was left in that location. This makes the belt a poor quarry from which to build the terrestrial planets. The current view is that the Earth and the other terrestrial planets accreted from a hierarchy of planetesimals of varying sizes, a process taking perhaps 50 to 100 million years. The noble gases (He, Ne, Ar, Kr, and Xe) and hydrogen are strongly depleted in the Earth relative to solar abundances. By the time the Earth, Venus, Mars and Mercury accreted, the gaseous components of the nebula were long gone. The hydrogen and helium gas in the nebula is swept away on time scales of 3–10 million years. The cause of this early volatile loss in the inner portions of the solar nebula appears to be connected with intense solar activity (T Tauri and FU Orionis stages) around the time that the early Sun joined the main sequence stage of stellar evolution.

Because of the differences in planetary compositions, there appears to have been little lateral mixing in the nebula. The terrestrial planets either accumulated from rather narrow (perhaps <0.5 A.U.) concentric zones in the solar nebula or from different populations of planetesimals. The present asteroid belt has a zoned structure, ranging from apparently differentiated objects in the inner belt, to apparently primitive ones which dominate in the outer reaches. Although the zones in the asteroid belt have been broadened through time by collisions, they may be an analogue for the original structure of the nebula.

Formation of the Moon: consequences for the Earth

The Earth's Moon is a unique satellite; the satellites of the other outer planets are mainly rock–ice mixtures, formed by accretion around their parent planets, or by subsequent capture. None of the other terrestrial planets except Mars possesses moons, but Phobos and Deimos, the tiny Martian moons, are probably captured asteroids. The lunar orbit is neither in the equatorial plane of the Earth nor in the plane of the ecliptic, but is inclined at 5.1° to the latter. The Moon has a high mass relative to that of its primary planet, compared with the satellites of the giant planets. The bulk density of the Moon (3.34 g/cm^3) is much less than that of the Earth (5.54 g/cm^3) or of the other inner planets. It is attributable to a low metallic iron content. The angular momentum of the Earth–Moon pair is anomalously high compared with that of the other inner planets. Some event or process spun up the system, although it is not rotating rapidly enough for classical fission to occur.

The Moon has an unusual composition by either cosmic or terrestrial standards. It is strongly depleted in volatile elements (eg. K, Pb, Bi) by a factor of about 50 compared to the Earth, or 200 relative to primordial solar nebula abundances, and is enriched in refractory elements (e.g. Ca, Al, Ti, U) by about a factor of 1.5 compared with the Earth. This has been confirmed recently by the data from the Clementine Mission (Lucey et al. 1995). The bulk lunar composition contains about 50% more FeO than current estimates of the terrestrial mantle. The Moon is bone dry, no indigenous H_2O having been detected at ppb levels (Taylor 1982).

No previous theories of lunar origin (capture, fission or double planet) survived the encounter with the Apollo sample data. A giant collision is now thought to be the most likely explanation for the origin of the Moon. The theory proposes that during the final stages of accretion of the terrestrial planets, and when the Earth was close to its present size, it suffered a grazing impact, at about 5 km/sec, with an object about 0.14 Earth masses (i.e. over 30% larger than Mars). Both this body and the Earth are assumed to have differentiated at that stage into a metallic core and silicate mantle. The collision disrupted the impacting body, much of which went into orbit about the Earth. Gravitational torques due to the asymmetrical shape of the Earth after the impact were sufficient to accelerate material into orbit. The core of the impacting body accreted to the Earth within about 4 hours. Most of the metal core ended up in the Earth, with the metal penetrating the mantle and ending up wrapped about the Earth's core (Taylor 1987).

The material out in lunar orbit either immediately coalesced to form a totally molten Moon, or broke up into several moonlets that subsequently accreted to form a partly molten Moon. At least half the Moon was molten shortly after accretion, with the feldspathic highland crust crystallising from this 'magma ocean'. The impact event was sufficiently energetic to vaporise much of the material which subsequently recondensed to make up the Moon. This explains such unique geochemical features as the bone dry nature of the Moon, the extreme depletion of very volatile elements and the enrichment of refractory elements in the Moon.

What were the implications for the Earth of the single impact origin of the Moon? The event probably triggered or enhanced complete mantle melting. However, the accretion of the Earth from large planetesimals, rather than fine dust, virtually guaranteed planetary melting, since the heat dumped in by such events cannot readily be lost.

Core, mantle, hydrosphere and atmosphere

The current scenario is that separation of the metallic core from the silicate mantle appears to have occurred promptly following the accretion of the Earth. Possibly, core formation was effectively coincident with accretion. No early sialic crust formed. Since the terrestrial planets accreted from planetesimals which were already mostly differentiated into metallic and silicate phases, little further reaction between metal and silicate may have occurred once these bodies accreted to the Earth. Possibly, the iron cores in the planetesimals were still molten

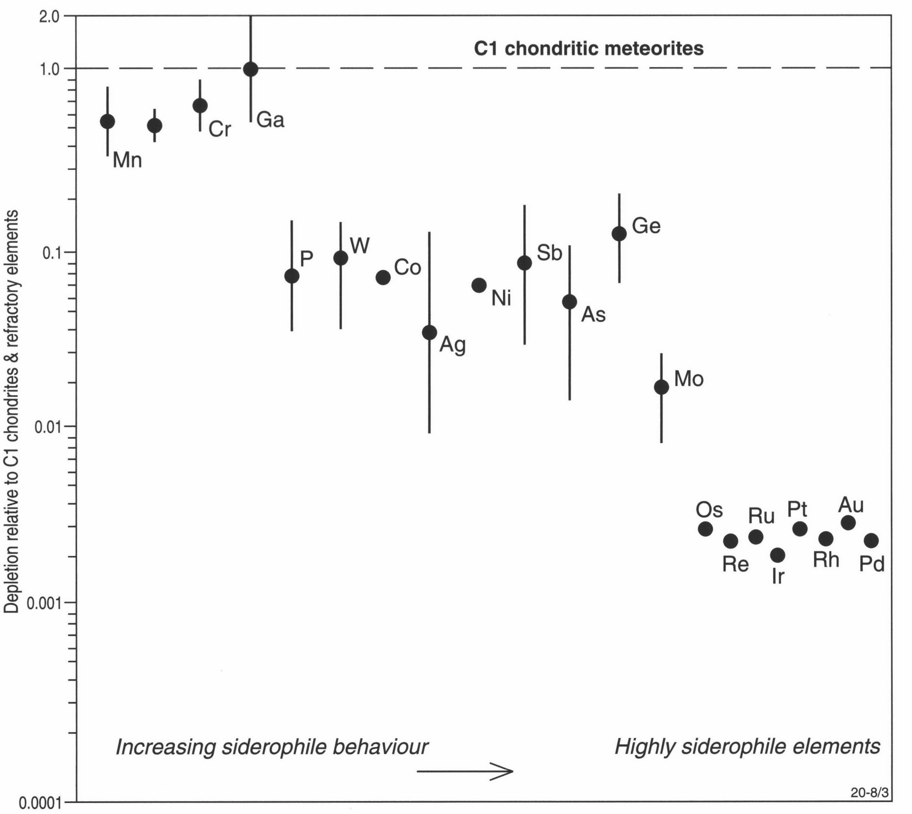

Figure 4. The abundance of siderophile elements in the upper mantle of the Earth, and in the Moon, normalised relative to primitive CI concentrations. The relatively high levels of Ni and Co, and the uniform 'chondritic-type' abundance pattern of the highly siderophile elements, indicate a lack of equilibration between the silicate mantle and the metallic iron core (courtesy of H.E. Newsom).

when they accreted to the Earth. In this model, core formation is effectively instantaneous and coeval with accretion, rather than occurring over hundreds of millions of years. However, melting of large planetesimals and their accretion to the Earth is likely to occur over a period of 50 to 100 million years, and separation of metal may have been delayed for such a period. This would be consistent with recent data from the decay of ^{182}Hf to ^{182}W that suggests such a time interval (Lee et al. 1995).

In addition, Re, Au, Ni, Co and the platinum group elements (Ru, Rh, Pd, Os, Ir, Pt) are highly abundant in the upper mantle of the Earth (Fig. 4). Thus the present upper mantle did not achieve equilibrium with the core. The distribution of platinum group elements appears to be rather uniform, and they are present in approximately primordial ratios, although depleted relative to iron. Their abundances are determined from samples only from the top 100 to 200 km of the mantle, so the composition of the lower mantle is essentially unknown.

A common explanation for the overabundance of platinum group elements in the upper mantle is that they result from late accretion of planetesimals rich in platinum group elements. A similar scenario of late accretion of volatile-rich planetesimals is commonly invoked to account for the volatile (e.g. H_2O) inventory of the Earth. A cometary influx could be an equally viable source. Another possibility is that the present abundance of highly siderophile elements in the Earth's mantle is due to addition of a small portion of the core of the lunar-forming impactor; the rest of the impactor's core accreted to the Earth's core without significant interaction with the Earth's mantle.

The metallic Fe/Ni outer core of the Earth contains about 10% of a light element. If high-pressure core–mantle equilibrium was not attained in the early Earth, then it seems unlikely that oxygen entered the core, since this requires megabar pressures, as is the case for potassium. Sulphur then becomes a possible candidate for the light element in the Earth's core. However, sulphur is a volatile element and the terrestrial budget may be inadequate. Other possible candidates are silicon and carbon.

Large collisions in the final stages of accretion are likely to have removed any primitive atmosphere which might have formed. The Earth accreted long after the hydrogen and helium, the principal components of the primordial solar nebula, had been dissipated and there is no sign of any primitive atmosphere. The present atmosphere and hydrosphere of the Earth appear to be entirely secondary in origin, formed by degassing from the interior or by late accretion from comets and asteroids from beyond Mars.

The isotopic composition of the noble gases helium, argon and xenon have provided crucial evidence that there was a sudden early degassing or outgassing event. Early extensive degassing is indicated by the noble gas data, which indicate that the mean atmospheric age is greater than 4 billion years. Thus most of the primitive volatiles were degassed from the mantle in the first half billion years after accretion, before there was significant addition to the mantle of ^{40}Ar from the decay of radiogenic ^{40}K. The xenon data indicate that up to 80% of the degassing occurred within about 50 million years following accretion. This early rapid degassing would be consistent with a molten mantle, that resulted both from the accretion of large planetesimals and from the formation of the Moon by a massive collision with the Earth.

Water was about twice as abundant as 'rock' in the primordial solar nebula. Since water either was never condensed or was lost along with the other volatiles in the early solar heating event, little water was available in the zone from which the Earth and the other inner planets were formed. Thus the source of water now in the Earth is an interesting problem. However, the total water content of the Earth is probably less than 500 ppm, an amount so small in comparison with the abundance of water in the early nebula that it could be ignored to a first approximation, except for our total dependence on it. Some water, perhaps present in hydrated minerals in already formed planetesimals, might have survived the early intense heating which drove the volatiles out of the inner solar system. Most probably came as a late-accreting veneer from beyond Mars since the minerals in the early nebula appear, from the meteorite evidence, to have been anhydrous. The late veneer that supplied the excess platinum group elements to the upper mantle is one possible source.

Water-ice is expected to be a stable phase in the nebula only at temperatures below 160K at nebula pressures. This means that water ice will occur only beyond 4–5 A.U. from the sun, in the outer reaches of the asteroid belt. This is consistent with the observation that icy satellites are restricted to the region of the giant planets. Carbonaceous chondrites, probably typical of asteroid compositions beyond about 3 A.U. contain up to 20% water by weight. Thus most of the terrestrial water was possibly derived from planetesimals or comets from beyond Mars, perhaps late in the accretional history of the Earth. If comets comprised 10% of the bodies responsible for the bombardment between 4.4 and 3.8 billion years they could supply the appropriate amount of water for the terrestrial oceans. Such a model is not without problems, since comets impact at high velocity, and so may remove earlier atmospheres and hydrospheres.

References

Binzel, R.P., Gehrels, T. & Matthews, M.S., 1990. Asteroids II. University of Arizona Press, Tucson.

Humayun, M. & Clayton, R.N., 1995. Potassium isotope chemistry: genetic implications of volatile element depletion. Geochimica et Cosmochimica Acta, 59, 2131–2148.

Kerridge, J.F. & Matthews, M.S., 1988. Meteorites and the early solar system. University of Arizona Press, Tucson, 1269 pp.

Lee, D.-C. & Halliday, A.N., 1995. ^{182}Hf-^{182}W chronometry, terrestrial core formation and early solar system evolution. EOS, 76, F338 (abstract).

Levy, E.H. & Lunine, J.I. 1993. Protostars and planets III. University of Arizona Press, 1293 pp.

Lucey, P.G., Taylor, G.J. & Malaret, E., 1995. Abundance and distribution of iron on the Moon. Science, 268, 1150–1153.

Newsom, H.E. & Jones, J.H., 1990. Origin of the Earth. Oxford University Press, New York, 378 pp.

Taylor, S.R., 1982. Planetary science: a lunar perspective. Lunar and Planetary Institute, Houston, Texas, 481 pp.

Taylor, S.R., 1987. The origin of the Moon. American Scientist 75, 469–477.

Taylor, S.R., 1992. Solar system evolution: a new perspective. Cambridge University Press, 307 pp.

Wasson, J.T., 1985. Meteorites: their record of solar-system history, Freeman, NY, 267 pp.