Geochemical implications of the formation of the Moon by a single giant impact

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The origin of the Moon by a single massive impact of a body slightly larger than Mars with the Earth can explain the angular momentum, orbital characteristics and unique nature of the Earth–Moon system. The density and chemical differences between the Earth and the Moon are accounted for by deriving the Moon from the mantle of the impactor. A cosmochemically plausible impactor can be formed in the region of the inner Solar System, lending support to the impact hypothesis.

THE Earth-Moon system has several unique features. None of the other terrestrial planets possesses a comparable moon—the tiny martian moons, Phobos and Deimos, are probably captured asteroids. The angular momentum of the Earth-Moon pair is anomalously high compared with that of the other inner planets, and the inclination of the lunar orbit is strange. The Moon has a high mass (1/81.3) relative to the Earth when compared with the satellites of the giant planets, but its bulk density ($3.34\,\mathrm{g\,cm^{-3}}$) is much lower than that of the Earth or the other inner planets, probably because of a low metallic iron content.

The chemical composition of the Moon, revealed by the samples from the Apollo and Luna missions, is also unusual. The Moon is bone dry, is strongly depleted in volatile elements such as potassium, lead and bismuth, and probably enriched in refractory elements such as calcium, aluminium, titanium and uranium (see box). In bulk, it contains ~50% more FeO than the upper mantle of the Earth.

In view of this diverse set of properties, it is perhaps not surprising that theories for the origin of the Moon have generally been unsatisfactory. Only recently has a model been proposed that is widely considered to be acceptable: the single impact hypothesis. This theory proposes that during the final stages of the accretion of the terrestial planets, a body somewhat larger than Mars collided with the Earth and spun out a disk of material from which the Moon formed. Here we will review the evidence for this theory and show how it can account for the unusual chemical composition of the Moon.

Older hypotheses

Including the single impact theory, there are five main classes of hypothesis for the origin of the Moon, although elements of some appear in others. The four older hypotheses fail to explain the unique nature of the Moon because they do not account for the lunar orbit or the high angular momentum of the Earth-Moon system, and because they entail processes that might have been common in the early Solar System, implying that similar satellites should accompany all the inner planets.

Capture of an already formed Moon from an independent orbit is improbable on dynamical grounds[1] and does not explain the compositional peculiarities, as the Moon would be expected to be an example of a common early Solar System object[2].

Formation of the Earth-Moon system as a double planet immediately stumbles on the difficulties of density and composition. To overcome the density problem, co-accretion was proposed[3]; in this model the Moon formed from a ring of low-density silicate debris shed from the mantles of incoming differentiated planetesimals, whose iron cores survived to accrete with the Earth. Although attractive, this scenario is improbable[1] because the breakup of planetesimals is unlikely to occur and it is difficult to achieve the required angular momentum[4]. In a similar model for co-accretion and evolution of a circum-terrestrial disk[5,6], it has been shown that the angular momentum is attained only in very special conditions.

Fission hypotheses, which derive the Moon from the terrestrial mantle[7], have been popular because they explain a low-density, metal-poor Moon, but they had to be abandoned after lunar samples showed significant differences in chemical composition between the Moon and the Earth's mantle[8]. A modification of this hypothesis[9,10] suggests that mantle material was thrown into orbit by many small impacts. Apart from the inherent chemical difficulties, it is exceedingly difficult to obtain the required angular momentum this way[1,11]. A further elaboration of this proposal, involving capture of objects in heliocentric orbits by an extended Earth atmosphere[9], is not supported by existing evidence[8,12,13], and this model also fails to account for the unique status of the Moon.

Single impact hypothesis

Formation of the Moon as the result of a single collision of a large body with the early Earth resolves many of these problems. The theory was first proposed to account for the anomalous angular momentum[14], but also provides an explanation for the other properties and has now become widely accepted[15].

In assessing the single impact theory, one must first ask whether a suitably large body existed in the early Solar System (before 4.4 Gyr). One scheme for the origin of the terrestrial planets[12], in which they are accreted from a suite of rocky planetesimals over a period of 10^7-10^8 yr, leads to a hierarchy of large bodies. In the final stages of accretion, perhaps 100 objects of lunar mass, 10 of the mass of Mercury and a few Mars-sized bodies populate the inner Solar System[12] before being swept up into the four inner planets.

There is considerable evidence for this scheme. Craters and ringed basins over 1,000 km in diameter on the Moon, Mercury, Mars and the satellites of the outer planets[16] attest to an early (>3.8 Gyr) intense bombardment by a large range of objects. The axes of nearly all the planets are significantly tilted relative to the plane of the ecliptic; the most dramatic example is Uranus, which is lying on its side, probably as a result of a collision with an Earth-sized object. The slow backward rotation of Venus, unique in the Solar System, is most rationally attributed to a

Classification of the chemical elements

To describe the behaviour of the elements in the solar nebula, cosmochemists divide them according to their volatility (examples in parentheses): 'gaseous' (hydrogen, carbon, nitrogen, oxygen and the noble gases), 'very volatile' (bismuth, thallium), 'volatile' (rubidium, caesium), 'moderately volatile' (potassium, manganese), 'moderately refractory' (vanadium, europium), 'refractory' (calcium, aluminium, uranium, lanthanum) and 'super-refractory' (zirconium, scandium). The terms lithophile, chalcophile and siderophile describe those elements that preferentially enter silicate, sulphide or metal phases, respectively. This classification is based primarily on the distribution of elements in these phases in meteorites.

late collision with a massive, perhaps Mars-sized object; with a different mass, angle and velocity, the impact might have provided Venus with its own moon.

Further evidence comes from the varied compositions of the planets; accretion from a dusty nebula, rather than from planetesimals, might be expected to produce rather uniform planetary compositions. Meteorites, too, come from many distinct parent bodies and are commonly mixtures of several components, or fragments of larger bodies. The asteroid belt, arrested at an early stage of planetary development, probably owing to the gravitational influence of the gaseous giant Jupiter, preserves a wide size range of objects (the largest, 1 Ceres, is 1,020 km in diameter). Finally, Mercury's anomalously high density and large iron core are most simply explained by removal of most of its silicate mantle by collision with a large body[17]; alternative schemes involving high-temperature evaporation of silicates remove unrealistic amounts of material[18] and do not account for the presence of sodium ions, probably sputtered from the surface, in Mercury's tenuous atmosphere[19].

Impact dynamics

Studies of the single impact hypothesis[20-26] have led to the following sequence of events (see Fig. 1). When the Earth had attained nearly its present size, it suffered a grazing impact, at about 5 km s^{-1}, with an object of ~0.14 Earth masses, somewhat larger than Mars[20,21]. Both this body and the Earth are assumed to have differentiated into a metallic core and silicate mantle. The collision disrupts the impactor, much of which goes into orbit around the Earth, accelerated by the gravitational torques arising from the asymmetrical shape of the Earth following the impact[20,21], and by expanding gases from the vaporized part of the impactor[14,23]. While the impactor's mantle is being accelerated away from the Earth, its metallic core separates from the mantle, decelerates, and accretes to the Earth in about four hours[22].

The material that achieves orbit is initially present as a disk partly inside and partly outside the Roche limit (~2.9 Earth radii)[22,25,26]. Some of the material inside the Roche limit ends up outside through transfer of angular momentum. The material may immediately coalesce to form a totally molten Moon, or break up into several moonlets which then accrete to form a partly molten Moon[26]. Geochemical studies indicate that at least half the Moon was molten shortly after accretion, with the feldspathic highland crust crystallizing from this 'magma ocean'[27]; in general, a partly rather than fully molten Moon seems most consistent with geochemical and geophysical constraints[26].

Lunar composition

Only a small amount of material from the Earth's mantle (probably less than 16%[20,22]) eventually ends up in the Moon. This is supported[8] by the low FeO content of the terrestrial mantle (8%) as compared with the Moon (13%), which would otherwise require that the FeO content of the impactor mantle be unreasonably large (≫13%)[28]. A Moon formed from 85% impactor mantle and 15% terrestrial mantle requires an impactor mantle with 14% FeO.

Additional evidence that there is relatively little terrestrial mantle material in the Moon comes from the isotopic composition of potassium[29]. Because the Moon is depleted in volatile elements relative to the Earth's mantle, the mass fractionation due to volatile loss should have left the Moon enriched in the heavier potassium isotopes. The fact that the isotopic composition of potassium in lunar feldspars is close to that of CI carbonaceous chondrites, considered to be typical of the solar nebula[29], limits the contribution from the Earth's mantle to <20%.

Relative to chondritic abundances (see Fig. 2 legend for a discussion of the use of carbonaceous chondrites as 'benchmarks'), the Moon and the Earth's mantle show similar depletion patterns of vanadium, chromium and manganese[9,30]. These contrast with the more chondrite-like abundances inferred for the parent bodies of the eucrite and shergottite meteorites, and are considered by some[9,10] to support an origin of the Moon from the Earth's mantle. But the depletion of Mn relative to V and Cr in the Earth and the Moon is also consistent with volatility having been the primary control on the abundance pattern[31,32]. New experiments on partitioning of these elements between sulphur-rich metallic liquid and silicate melt[31,32], confirming earlier work on partitioning between pure iron metal and silicate melt[33,34], as well as data for Cr and Mn in natural metal–silicate rocks from Disko Island[35], show that V and Cr are more highly siderophile (literally, 'iron-loving'; see box) than Mn. Thus, had these elements been depleted by core formation in the Earth, we would see a greater depletion of V and Cr compared to Mn, contrary to observation. Their depletion in the Earth's mantle, therefore, cannot be ascribed to unique terrestrial processes involving formation of the Earth's core[9,36], and similar depletions of V, Cr and Mn in the Earth and Moon do not require that the Moon formed primarily from terrestrial mantle material.

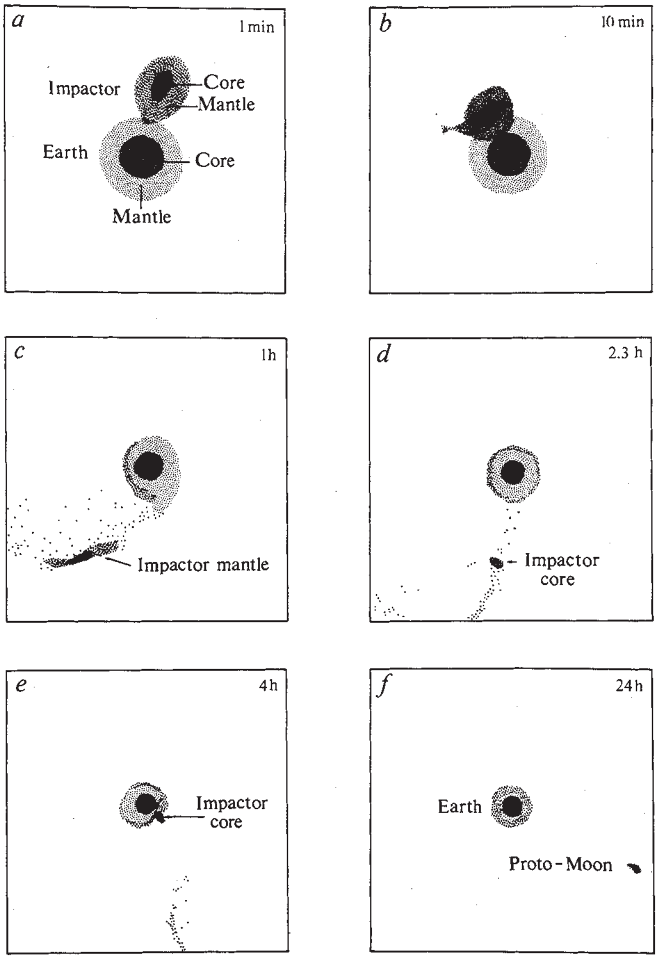

FIG. 1 Computer simulation[20–22] of the formation of the Moon by a giant impact. This reconstruction shows the events following the oblique collision with the Earth of an object of 0.14 Earth masses (slightly larger than Mars) at a velocity of 5 km s^{-1}. Both the Earth and the impactor have already differentiated into a metallic core and silicate mantle. The time elapsed since impact is given in each box. Following the collision (*a*, *b*), the impactor is spread out in space (*c*), but the debris clumps together through gravitational attraction. The iron core of the impactor separates from the silicate mantle (*d*) and accretes to the Earth (*e*) about four hours after the initial encounter. Nearly 24 hours later (*f*), a silicate lump of about lunar mass is in orbit around the Earth. This material is principally derived from the silicate mantle of the impactor. Courtesy of A. G. W. Cameron and W. Benz.

Constraints on impactor composition

What can be deduced about the composition of the impacting body? We will first consider the constraints on the lithophile and volatile element composition of the impactor, and then use the siderophile element depletion patterns in the Earth and Moon to derive the siderophile abundances in the impactor's mantle and the size and composition of the impactor's core. We assume[20-22] that the impactor was 0.14 Earth masses, and was differentiated into a metallic core and silicate mantle. We also assume that it formed in the same part of the solar nebula as the Earth (between Venus and Mars), to account for the low relative impact velocity (5 km s^{-1}; ref. 23) and the similarity in oxygen isotopes between Earth and Moon. Although there was probably much mixing of planetesimals during their formation, the terrestrial planets retain some memory of having accreted from relatively narrow (<1 AU) feeding zones, a notion supported by the zoned compositional structure of the asteroid belt[37].

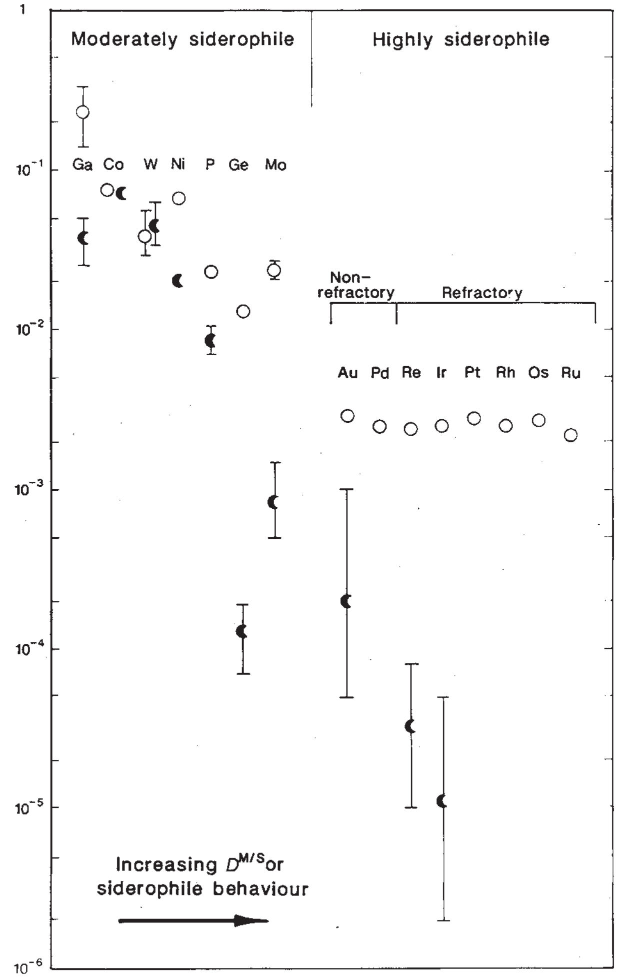

FIG. 2 Depletion of siderophile elements in the Earth (○) and Moon (☾)[42,51], plotted in order of metal/silicate partition coefficient, $D^{M/S}$. The dividing line between moderately and highly siderophile behaviour is taken to be $D^{M/S}=$ 10,000, meaning that the element is partitioned into the metallic phase with a concentration ratio (metal:silicate) of 10,000:1. The depletions are normalized to abundances in CI chondrites relative to aluminium, because the non-siderophile refractory elements are enriched in the Earth and Moon. The greater depletion of gallium and germanium in the Moon relative to elements with similar siderophile behaviour is probably due to their volatility. Elemental abundances in Solar System objects are usually expressed relative to those in the primitive, volatile-rich meteorites known as CI chondrites. For the non-gaseous elements, these meteorites give the best estimate of the composition of the Sun, and thus of the primitive solar nebula from which the planets formed[56]. Primitive material, unchanged since the formation of the solar nebula, would have flat or 'chondritic' patterns; conversely, any deviation from chondritic abundances (or relative abundances) provides information about an object's chemical history.

Lithophile and volatile elements. The constraints imposed by these elements on lunar origins and the single impact hypothesis are only briefly summarized here; for more details, see ref. 8. The impact was sufficiently energetic to vaporize much of the material that went to make up the Moon, explaining such unique features as the bone-dry nature of the Moon and the extreme depletion of very volatile elements. Bismuth and thallium, for example, are depleted by factors of ~200 relative to cosmic abundances. Elements that are volatile at temperatures above ~1,100 K (such as europium and ytterbium) do not appear to be depleted in the Moon[8], setting an upper limit on the temperature experienced by proto-lunar material.

If the impactor formed in the region of the terrestrial planets, then it must have been somewhat depleted in volatile elements, as there was an earlier, if less dramatic, depletion of these elements in the inner solar nebula. This is shown by the low volatile/refractory element ratios (for example, $K/U=(1\text{-}2)\times 10^4$) in the Earth, Venus and Mars, compared with initial solar nebula values of 6×10^4.

This depletion event must have occurred very soon after the formation of the Solar System ($T_0=4.56$ Gyr), as shown by the low initial $^{87}Sr/^{86}Sr$ ratios in meteorites[38,39], which indicate a very early separation of volatile rubidium from refractory strontium. Also, the lunar initial $^{87}Sr/^{86}Sr$ ratio is close to that of the basaltic achondrites—meteorites which formed as igneous rocks 4.54 Gyr ago[38,39]; thus, lunar ^{87}Sr must have evolved in a low-Rb/Sr environment from times close to T_0.

Accordingly, the Rb/Sr ratio was probably lower than chondritic in the lunar precursor material. As the Earth, the Moon and the CO, CM and CV carbonaceous chondrites display similar V-Cr-Mn patterns (see above), this widespread volatility-related depletion may have been caused by early volatile depletion in the nebula, rather than the giant impact. It seems safe to conclude that the impactor mantle was not composed of material with the composition of CI chondrites, but had undergone a volatile depletion similar to that seen elsewhere in the inner Solar System[8,37], and thus had Rb/Sr ratios, V-Cr-Mn patterns and K/U ratios similar to those of the inner planets; additional potassium, other volatile elements and water were lost in the collision. The physics of volatile depletion during lunar formation needs further study[25].

The bulk Moon is probably enriched in refractory elements (such as Al, Ti, Ca and U) by a factor of 1.5 compared with the terrestrial mantle, or about 2.5 times the primitive abundances in CI meteorites. The geochemical arguments for this[8] have been buttressed by geophysical studies, which support a high-alumina Moon[40]. The most recent refinement of the geophysical data[41] concludes that "only in the case of extreme assumptions can critical aspects of bulk lunar composition be demonstrated to be equivalent to the present-day terrestrial mantle: specifically the Moon has an Mg#[$=$Mg/Mg+Fe] that is too low and an alumina abundance that is too high".

Whether the mantle of the impactor was enriched in refractory elements is less certain; alternatively, fractional condensation from a vapour phase could have enriched the Moon in alumina, uranium and the other refractory elements[8]. But such a process might alter isotopic ratios, and no such effects have been observed in the potassium isotopes[29]. We conclude that the impactor was probably enriched in refractory elements, noting that the Earth is enriched over CI abundances by a factor of 1.5. This raises broad questions about the relative compositions of the terrestrial planets, selective accretion from already differentiated planetesimals, and the effects of massive collisions that remain for future research.

Siderophile elements. The depletion patterns of siderophile elements in the Earth and Moon (Fig. 2) provide constraints on their abundance in the mantle of the impactor and on the size of the impactor's core. Two important characteristics of the siderophile abundances in the Earth's upper mantle are that the highly siderophile elements (such as rhenium and iridium) seem to be uniformly distributed throughout the upper mantle, and have chondritic relative abundances (Fig. 2). These facts are often attributed to accretion of a late (post-core-formation) veneer of meteoritic material to the terrestrial upper mantle[45], because the siderophile element concentrations are too high to have been in equilibrium with a metallic core.

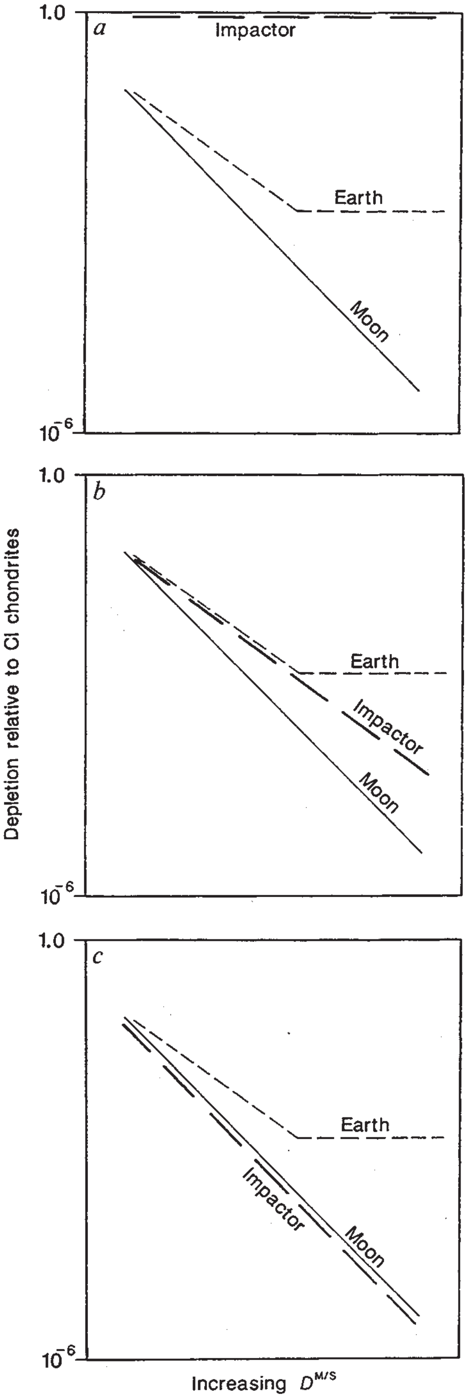

FIG. 3 Schematic siderophile element depletion patterns for the Earth and Moon, resulting from different siderophile depletion patterns in the impactor mantle. *a*, An impactor resembling a chondritic meteorite, with no segregation into metallic core and silicate mantle. *b*, An impactor mantle with a siderophile element pattern similar to that of the Earth's mantle, without the 'late veneer' of highly siderophile elements. *c*, An impactor with a siderophile element depletion pattern similar to that of the lunar mantle.

The lunar siderophile pattern, by contrast, shows a relatively uniform decrease in abundance (relative to chondrites) of the refractory siderophile elements as a function of their siderophile nature. (Elements such as gallium and phosphorus may also be depleted owing to their volatility.) This depletion pattern is quantitatively consistent with equilibrium between the lunar silicates and Fe-rich metal at low degrees of partial melting[42], presumably during core formation. (The existence of a lunar core of 350–500 km radius, although not conclusively proven, is consistent with many geophysical data, including the Moon's moment of inertia coefficient[43], electrical conductivity, and the latest assessment of lunar palaeomagnetism, which seems to require a dynamo in an electrically conducting core between ~4 and 3.5 Gyr ago[44].) Only the least siderophile elements, such as tungsten and cobalt, are similarly depleted in the Earth and Moon.

The conclusion that core formation can explain the lunar siderophile abundances depends on the lunar core having a relatively low nickel content (<10 wt%[42]). A nickel-rich core would be less efficient at scavenging siderophiles from the silicate phase; thus, if the lunar core were in fact to contain 41 wt% Ni, as has recently been suggested[46], the Moon's siderophile depletion would have to be explained by its formation largely out of material from the Earth's (already depleted) mantle. We do not feel that this conclusion is required, however, because the figure of 41% was derived from the Ni abundance in Apollo 15 green glass, assuming[46] that this glass represents a liquid from the primitive lunar mantle. In fact, the chemistry of the glass—notably its depletion in europium and strontium, characteristic of other lunar mare basalt samples[27]—indicates that its source region was formed by crystallization from the lunar magma ocean. If this magma ocean was in direct equilibrium with the lunar core, then the Ni content of the green glass would indeed reflect that of the lunar core. This is unlikely, however, because the metal separation would have occurred at some moderate degree of partial melting, whereas the magma ocean probably represents a high degree of melting of the lunar mantle. Assuming that a large proportion of the Moon (or precursor planet) experienced metal segregation at 10% partial melting, following which the silicates were partially or completely melted to form a magma ocean, the nickel content of the metal in the lunar core could range from 10 to 27 wt%.

An additional argument against Ni-rich metal in equilibrium with lunar silicates comes from the very reduced oxidation state of the Moon, which is characterized by a total lack of ferric iron. Lunar basalts crystallized at oxygen fugacities four to five orders of magnitude lower than those of terrestrial basalts at equivalent temperatures[47]. If lunar silicates had equilibrated with Ni-rich metal, lunar oxygen fugacities would be much higher.

The lunar siderophile element pattern allows four possibilities for the siderophile abundances in the impactor, the implications of which are discussed next. The second and third cases seem most plausible.

An undifferentiated impactor. The least likely possibility is that the impactor had chondritic abundances of siderophile elements in its mantle; that is, there was no separation of metal from silicate (Fig. 3*a*). Not only would the lunar iron content derived from such a source be too high, but it is hard to see how a planet larger than Mars could escape differentiation into a separate core and mantle[48]. There is abundant evidence from over 60 varieties of iron meteorite that core formation occurs even in relatively small asteroidal bodies. Also, the absence of a core in the impactor would make it more difficult to place a lunar mass of material in orbit[20–22]. The objections to an undifferentiated chondritic impactor, and to an oxidized chondritic impactor containing no Fe–Ni metal, are discussed in more detail in ref. 49.

In this model the entire siderophile element depletion observed in lunar silicates has to be explained by core formation

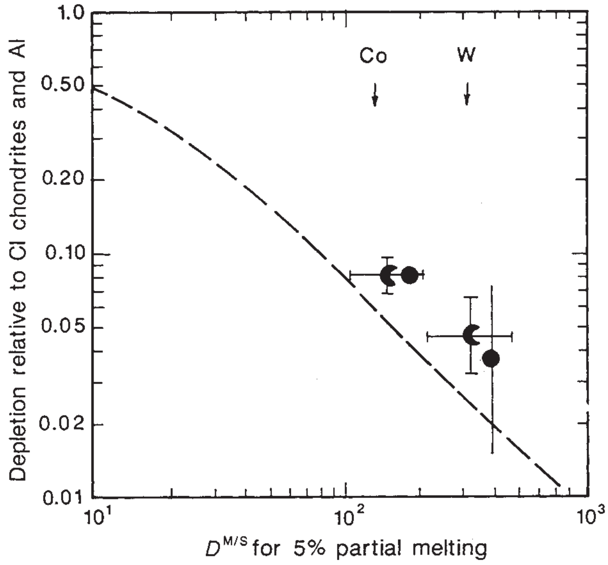

FIG. 4 The maximum core size in the impactor is constrained by the similar abundances of W and Co in the Earth (●) and Moon (☾). These imply that the impactor also had similar concentrations of W and Co. The maximum allowable core size (10 wt%) corresponds to the minimum metal/silicate partition coefficients ($D^{M/S}$) for these elements, and the maximum depletion[42]. The minimum partition coefficients are calculated for a composition of 50 wt% S-rich metal and 50 wt% Fe-metal[42,54]; a larger amount of S-rich metal would reduce the partition coefficient of W too much relative to Co. The maximum depletion for these elements is derived from estimates of the uncertainties of the depletions[42]. The dashed line represents the depletions expected for a core size of 10 wt%, and this line just grazes the maximum depletions observed in the Earth and Moon.

in the Moon. Newsom[42] concluded that the observed lunar depletion could be explained by segregation of $\sim$4-5.5 wt% Fe-Ni metal[40,41,50], assuming segregation at low degrees of partial melting of the silicates (5-9%).

Siderophile depletion in impactor mantle similar to Earth's mantle. With the exception of the highly siderophile elements (Fig. 3*b*), this could be produced by segregation of a small (<10 wt%) core, assuming equilibrium between the impactor's core and mantle. In the absence of core-mantle equilibrium, as in the Earth, any size of core would be possible, including 30 wt%[20-22]. If the Moon formed from material with a siderophile element pattern characteristic of the Earth's mantle, including Earth-like abundances of highly siderophile elements, then segregation of additional metal (<0.2 wt%) is needed in the Moon to produce the observed lunar pattern[42].

Siderophile depletion in impactor mantle similar to present Moon. Formation of the Moon from material with essentially its present abundance of siderophile elements constrains the amount of metal in the impactor that could produce the depletion. Assuming impactor core-mantle equilibrium and the largest possible depletion of Co and W in lunar silicates, the maximum size of the impactor core is $\sim$10 wt% metal (Fig. 4). The composition of the impactor core is also constrained by the Co and W abundances. The metal/silicate partition coefficients[51] are lower for sulphur-rich metal (25-30% S), allowing larger core sizes than for sulphur-free metal (Fig. 3*c*). Assuming that the impactor core consists of both S-rich and S-poor metal, the fraction of S-rich metal in the core must be <50%. A larger amount of S-rich metal would reduce the partition coefficient for W too much relative to Co, and W would not have been depleted, as is observed for the shergotite parent body[52,53]. In this model, no metal segregation in the Moon is required to explain the siderophile abundances. If a lunar core exists, as indicated by the geophysical data, there must have been disequilibrium between the core and the lunar mantle during core formation.

Siderophile depletion in impactor mantle greater than in the Moon. This possibility is unlikely, as it requires siderophile elements to be added to the Moon from elsewhere. The moderately siderophile elements Co and W have similar abundances in the Earth's mantle and the silicate portion of the Moon (Fig. 4). If the impactor had W and Co abundances significantly below the lunar (and terrestrial) level, addition of terrestrial material would not bring the abundance up to the lunar level. The abundances of the highly siderophile elements could be consistent with the addition of a relatively large amount of terrestrial mantle material to the Moon (15-50%), although additional complications arise if the Earth's mantle already possessed its veneer of highly siderophile elements.

Implications for the Earth

The implications for the Earth of the single impact origin of the Moon are considerable. The event probably triggered or enhanced complete melting of the Earth's mantle[26]. In addition to the accretion of the impactor's core, the impactor's mantle would have provided about 10% of the mass of the Earth's mantle.

For the second and third models above, with terrestrial or lunar siderophile abundances in the impactor, the implications for the siderophile element budget of the Earth depend on the fate of the metal core from the impactor. Models of the collision[20-22] indicate that most of the impactor core ends up in the Earth, with the metal penetrating the mantle and wrapping around the Earth's core. This would not disturb the siderophile abundance patterns already present in the Earth's mantle, but a significant amount of material from the impactor's core, enriched in siderophile elements, would probably have been vaporized and redistributed into the mantle. The detailed implications for terrestrial siderophile abundances depend on the fraction of the accreting metal core with small enough grain size to equilibrate with the mantle, but partial retention of metal from the impactor could explain the entire siderophile element pattern in the Earth's mantle[49,54]. Another variation on this theme states that the present abundances of highly siderophile elements in the Earth's mantle (the late veneer) result from the addition of a small portion of the impactor's core, while the rest of the impactor's core accreted to the Earth's core without significant interaction with the Earth's mantle. The Moon shows little evidence of a late veneer of siderophile elements, supporting an event unique to the Earth as the explanation for the abundances of the highly siderophile elements in the Earth's mantle.

To obtain the observed mantle abundances of the highly siderophile elements requires adding material with chondritic abundances equal to 0.74% of the mass of the Earth's mantle[55]. This can be achieved with 3-4% of the impactor's core, assuming that the total mass of the impactor is between 0.12 and 0.17 Earth masses, respectively. The percentage of the impactor core required depends on the size of the impactor, and is independent of the size of the impactor core because the highly siderophile elements from the impactor would be quantitatively concentrated in the metal. The amount of metal containing the siderophile elements added to the mantle is very small: 0.2 wt% of the Earth's mantle for an impactor core size of 31 wt%, and less than that for smaller cores.

As for the moderate siderophiles, the probable differentiation of the impactor into mantle and core would have depleted these elements in the impactor mantle to levels at or below terrestrial mantle values. Thus the addition of impactor mantle amounting to <10% of the mass of the terrestrial mantle would not significantly alter the terrestrial abundances of the moderately siderophile elements. The contribution of both moderately and highly siderophile elements from the impactor's core to the abundances in the Earth mantle would be only $\sim$1%, insignificant compared with the 5-10% levels in the Earth's mantle.

Conclusions

From these arguments we deduce that not only the dynamics, but the chemical properties of the Earth–Moon system can be explained by a low-velocity (5 km s^{-1}) collision with the Earth of a body of ~0.14 Earth masses (larger than Mars) during the final stages of the accretion of the Earth from a hierarchy of planetesimals. The impacting body was already differentiated into a metallic core and silicate mantle; the material that ended up in the Moon was derived principally from the impactor's mantle, which must have been depleted in siderophile elements by core segregation, leaving siderophile abundances somewhere between lunar and present terrestrial mantle values. The core of the impactor was <10% of its mass, if there was equilibrium between it and the mantle, and the fraction of S-rich metal in the impactor's core was <50% of the core's mass. The core might have been larger, if the core and mantle were not in equilibrium. The impactor's mantle had volatile-element abundances similar to those of the terrestrial planets, and was enriched in FeO compared to the Earth.

The fate of the impactor's core has important implications for the abundances of siderophile elements in the Earth's mantle. The chondritic relative abundances of the highly siderophile elements can be explained if ~3–4% of the impactor's core were mixed into the Earth's mantle, the remainder of the core accreting to the Earth's core without interacting with the mantle.

For fuller substantiation, the giant impact hypothesis requires more data, some of which can be collected only on future space missions. For example, the geochemical behaviour of the elements under the extreme conditions of the impact is poorly understood and it is not clear how much of the depletion of volatile elements and enrichment of refractory elements in the Moon is a result of the impact. To answer this, we need more information on the overall composition of the lunar surface, which could be obtained by an orbiting probe; additional data on heat flow, which would put constraints on bulk composition; and seismic measurements to determine the size of the lunar core and confirm the density discontinuity at 500 km depth. Future lunar missions might obtain direct samples of the lunar mantle from the central peak of Copernicus where mantle rock has evidently been exposed by rebound following the impact that formed the crater.

On Earth, we need to know more about the chemistry of siderophile elements in the mantle, and more about the lower mantle, which remains largely unexplored. Further from home, mechanisms of planetary accretion have to be examined. This will require an understanding of the variations in the composition of the original nebula, which can be estimated from the geochemistry of Mercury, Venus and Mars. The forthcoming exploration of the martian moon, Phobos, and probes to distinct regions of the asteroid belt may also provide insights into the formation of the now-vanished hierarchy of planetesimals that accreted to form the terrestrial planets, and of the one that provided us with our unique and poetically inspiring Moon. □

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