Impact origin of the moon – The probable scenario

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Early in the seventeenth century, Galileo described the moon as a rocky body like the earth, and since then several views on the origin of this planet-sized satellite of the earth have appeared. One of them, the 'capture theory', considered that the moon was captured into a circular orbit around earth after its formation elsewhere in the solar system. A second one, the 'co-accretion theory', considered that the moon formed at the same time as the earth out of differentiated planetessimals. According to a third view, the 'fission theory', it was formed from the material thrown out of fast-spinning molten early earth. While these views prevailed for some time, they were dismissed in the light of new data that emerged from samples of moon-rocks brought by the manned lunar exploration by USA between 1969 and 1972. The 'capture theory' was rejected as improbable on dynamical grounds and incompatibility with the composition of early solar system objects. The 'co-accretion theory' failed to explain the very small size of the moon's core and also satisfy the angular momentum (the rotational and orbital motion of objects in curved paths, here the earth–moon pair's spin plus the orbital motion of the moon around the earth) and likewise the 'fission theory' could not explain either the compositional differences, particularly presence of iron core, or the total angular momentum and energy involved in moon formation.

Besides dismissing all earlier speculations about the moon's origin, the moon-rock studies brought out the close agreement of these rocks to composition of the earth's mantle (except for the volatiles such as potassium, lead and bismuth). This similarity led to new thinking on possible genetic connection between earth and moon, and in 1975, for the first time, it was proposed that the moon formed as a result of a collision between a very large planet-sized body and the earth[1–3]. Such a massive impact event did not appear unlikely either, under the turbulent conditions that were known to have prevailed during the early stages in the evolution of planets[4]. The primordial cloud of gas and dust out of which the sun formed at the centre of the solar system, also gave rise to the 'building blocks of planets' – the planetessimals. Their accretion, a few million years after the formation of the sun[5], formed the inner rocky planets. Initially, the planetessimals were small and orbiting in roughly circular orbits, colliding mildly and growing in size through steady accretion, some of them up to a few hundred kilometres in diameter. During this phase of planetary formation, passage of large bodies close to other smaller ones exerted gravitational pulls on the latter, nudging them into elliptical paths and increasing their collisional speeds[4,6–8]. While collisions of small bodies on large planets were inconsequential, those of large bodies on the terrestrial planets produced catastrophic results. Such a collision between a large planet-sized body and the proto-earth is now thought to have ejected large amounts of material, mainly from the mantle region of both the earth and the impacting body (Figure 1). The ejected debris or cloud of rocks, the parent material for the moon, soon condensed, incorporating preferentially several refractory elements[6] like Ca, Al, Ti, U. This impact is supposed to have occurred when the earth was only 60–70% of its current mass[9]. By this time most of early earth's iron had already segregated into the core, which explains the iron-poor state of the moon.

The impact theory is now widely accepted as it answered many features of the earth–moon system such as the peculiarities of its bulk chemistry, its isotopic make-up and its high angular momentum. However, the following were not clear: at what stage of the earth's evolution did the giant collision occur or, what was the size of the impactor or impactors that could have produced the present geometry of the earth–moon system, or whether the moon that formed from the debris initially goes through a molten stage and whether this proto-moon was itself a target for impacts. Now, answers to these have come as a result of breakthroughs in computer technology that could simulate this collision and its effect, both on the impactor and the target. The likely early earth scenario could be recreated and studied sequentially, from the onset of the impact to several hours after, thanks to sophisticated software developed during the last few years. This software breakthrough has made it possible to evaluate the pre- and post-impact scenario in three dimensions, giving due importance to the complexities involved in such a dynamic event such as those concerning the angle of impact, impactor-to-target mass ratios, their angular momenta, generation of shock waves and their propagation, thermal changes that accompany like melting and vapourization, mutual gravitational interactions, and finally the condensation of debris to form the moon[5,10,11].

A computer simulation study carried out a few years ago concluded that an impactor larger than Mars struck the earth at a grazing incidence when earth had attained nearly its present size[12,13]. Both, impactor enriched in refractory elements and the target earth are assumed to have already differentiated into silicate mantle and metallic core. About < 16% of the earth's mantle is thought to have been ripped-off in the collision process which also disrupted the impactor[14]. While much of the mantle material, accelerated by gravitational torques of earth, went into orbit around the earth, the metallic core accreted to the earth. The material that attained an orbit around the earth, mostly from the impactor, gradually developed into the moon[13].

Now, in another very recent simulation model, researchers using very special methods simulated the growth of the solar system since its very early stages to development of proto-planets and their steady movement into their respective orbits. The studies showed that during the growth of the planets giant impact events were inevitable. In modelling of this moon-forming giant impact[11] that the earth underwent, they studied, unlike the earlier modellers, a larger population of ejected debris.

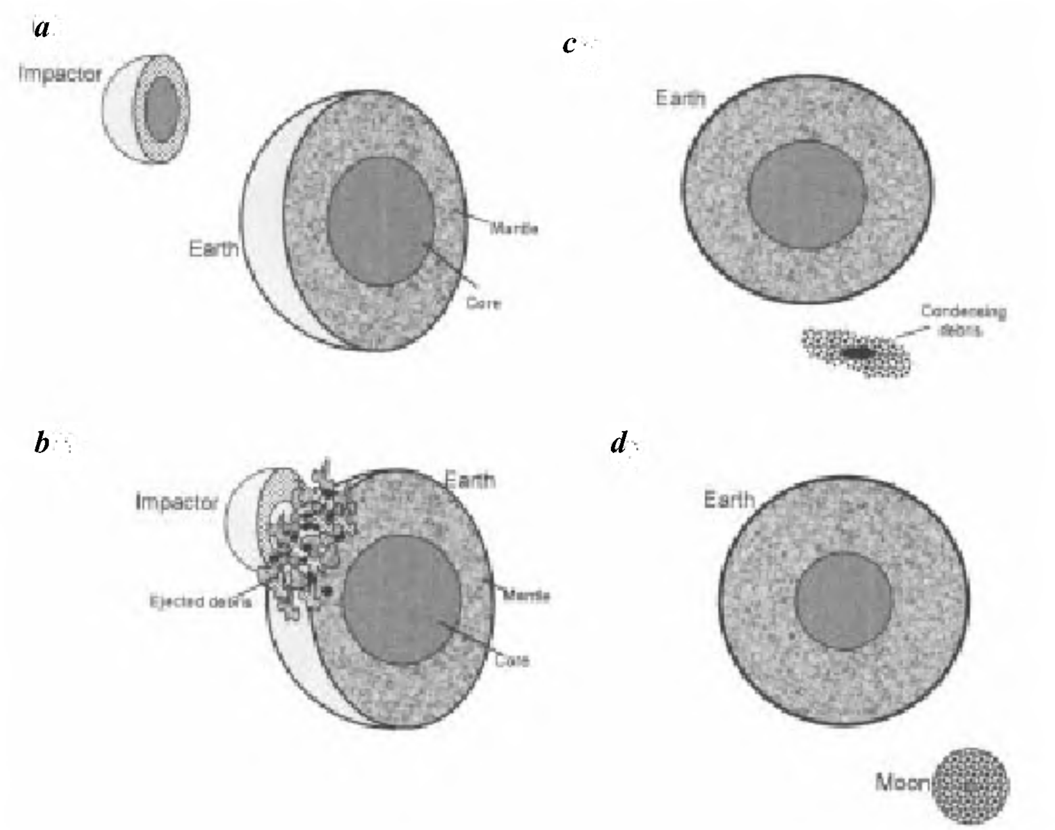

Figure 1. Moon-forming giant collision with early earth. ***a***, Large-sized differentiated impactor approaching earth for collision; ***b***, Impact at a low or grazing angle leading to disruption of impactor and ejection of debris, mostly from the impactor's mantle and lesser amount from the earth's mantle; ***c***, Ejected debris in orbit around the earth gradually condensing to form; ***d***, the moon in orbit around earth.

They concluded that for production of the present earth–moon system with poor iron and high angular momentum, smaller-sized impactors were involved. Very large impactors, they found, would produce a massive disk, which will yield an earth–moon system with too much angular momentum and create a lunar orbit much farther out. Working out various impactor-to-target mass ratios, these studies showed that impacts by smaller bodies are more likely to occur than 2–3 times more massive ones, as postulated by earlier workers and that an impactor of the size of Mars would be optimum[11,15]. Also, the studies report that the event must have taken place near the very end of the earth's accumulation and not early in earth's history as envisaged by some[9,16]. Impact-generated debris that went into orbit were mostly from the impactor, the target earth contributing mass only up to tens of per cent[11]. This implied that moon accreted primarily from an impactor, a view doubted by some on grounds of the moon's strong earth-like features[17].

Critics have pointed out that computer simulations have shortcomings and in the present case they believe that the quantity of debris thrown out must have affected the size and orbit of the resulting body[18]. But the latest studies[11] claim that the present class of impacts 'represents the least restrictive scenario, requiring little or no dynamical modification to the earth–moon system after the moon-forming impact'. Further, even though both earth and moon continued to receive post-collision showers of small impact, these, at best, could have only slowed down the rotation of the earth–moon system rather than increase the mass; but this is contested by a few whose calculations indicate a 4% increase in mass after moon-formation[19]. That the earth continued to receive impacts after moon-formation is gaining more acceptability, judged for example, from the existence of anomalous distribution of siderophile elements in the earth's mantle, particularly the highly siderophile noble metals. Their anomalous presence is attributed to targeting of the earth by such impactors, as 'late-veneer'[13,20–22], rich in core-forming metals. The continued impact events are also thought to have triggered episodes of magma oceans and core formation repeatedly.

Impact modellers and geochemists have discussed impact theory[9], particularly with regard to the enormous heat that may result from the impact event. This could have remelted the earth substantially, generating a magma ocean followed by fresh geochemical fractionation. But imprints of such fractionation of elements into solid or liquid phases have not been observed. This, according to one view, is unlikely to take place in a turbulently convecting impact-generated magma. The post-impact development of lunar magma ocean, on the other hand, is strongly supported by Hf-W isotopic sytematics[9,16] as well as by two moon-surface mapping space missions by USA[23]. Differentiation of this lunar magma ocean, during its formative first billion years or so resulted mainly in its anorthositic crust, magnesium-rich highlands and small amounts of basalts. Judged by the age of the lunar highlands, the moon must have formed and differentiated ~ 50 m.y. after the start of the solar system and between 4.4 and 4.5 b.y. ago[7,16], soon after the earth's core formation, i.e. during the first 100 m.y. of earth's history. Presently, though the origin of the moon as arising from a giant impact or an impactor which had a metal segregational history similar to earth is widely accepted, this postulate remains still a hypothesis. Perhaps, future work will be able to assess better the influence of various forces in operation during and after the giant impact event, involving areas of high-pressure physics, shock-related changes (melting and vapourization) and a host of other inter-related forces and confirm the impact origin of the moon.

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SCIENTIFIC CORRESPONDENCE

Effect of helpers on breeding success of the common babbler (*Turdoides caudatus*)

The effect of helpers on the breeding success of the common babbler (*Turdoides caudatus*) inhabiting the arid zone of Rajasthan has been studied. The aim of the present study is to determine the contribution of helpers in the breeding success of the common babbler. The role of helpers in the breeding activities of the common babbler like feeding of the brooding female, nestling and fledgling, and defending the nests, improves the clutch size, hatching success and fledgling success. The significance of the role of helpers has been discussed.

An extensive literature exists about helping in birds, where some reproductively mature or immature members of the species temporarily or permanently forego their own reproduction and help other members of their species to reproduce[1–5]. Brown's book[6] is the most extensive review of helping in birds. The Florida scrub jay (*Aphelocoma caerulescense*), the acorn woodpecker (*Melanerpes formicivorus*), the pied kingfisher (*Ceryle rudis*), the splendid wren (*Malurus splendens*), the Galapagos mockingbird (*Nesomimus parvulus*), the green bee-eater (*Merops orientalis*) and the white-fronted bee-eater (*Merops bullockoides*) have been extensively studied for helping in birds[7–9].

Among babblers, the role of helpers has been studied in the jungle babbler (*Turdoides striatus*), the Arabian babbler (*T. squamiceps*), the grey-crowned babbler (*Pomatostomus temporalis*) and the white-headed babbler (*T. affinis*)[8–12]. Common babblers have been studied for their habits, habitat and reproduction[13,14]. Yet no effort has been made to study the effect of helpers on the breeding success of the common babbler. An attempt was therefore made to study the effect of helpers on the breeding success of the arid-zone common babbler (*T. caudatus*).

Nests of common babblers without helpers, with one helper and with two helpers were observed for one year (2000) during the breeding months (February to August) at one sampling site (10 km^2) in the Khasoli agricultural fields, Churu (29°N, 75°E; rainfall