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The Moon's formation revisited

The falsification of a hypothesis and its replacement by a new testable hypothesis are part of progress in science. With respect to the formation of the Moon the classic Giant Impact Hypothesis (GIH) as described in the recent article by Geiss, Huber and Rossi, *Europhysics News* **45/4**, 25-30, was developed when other hypotheses had to be discarded after the first analyses of the composition of lunar rocks, returned to Earth in the Apollo missions. The GIH appeared to explain the first-order physical and chemical features of the Earth-Moon system, including its angular momentum and the depletion of iron in the Moon compared to the Earth. The GIH was not seriously challenged for over thirty years since its inception in the mid-1970s [1].

However, over the past decade, increasingly large cracks have appeared in the armour of the GIH. More precise analytical techniques have revealed an astonishing similarity in both the elemental and isotopic composition between lunar rocks and the Earth's silicate (rocky) crust and mantle. Similarities encompass major elements including silicon and titanium [2] as well as trace elements including neodymium and tungsten [3]. Such similarity is irreconcilable with smooth-particle hydrodynamic computer simulations of the classic giant impact of a Mars-sized planet into the young Earth, because those all predict that the Moon should consist predominantly of impactor material rather than of terrestrial material [4]. Several attempts have been made to fix this fundamental problem with the GIH. One suite of models has investigated whether lunar and terrestrial mantle material can be completely homogenised elementally and isotopically after the giant impact. The answer appears to be: not for all elements that show the uncanny Earth-Moon resemblance, and not for all of the silicate Earth and the Moon [5]. Collisional parameter space for giant impact models has also been stretched to try and fit the compositional similarities [6]. Impacts in which the impactor is either significantly smaller than Mars or as large as the Earth itself lead to predicted lunar compositions which are closer to that of the silicate Earth, more consistent with observations. But such impacts only work if they are accompanied by Earth-Moon system angular momenta that are significantly larger (by about a factor of 3) than today's values. Such momenta are actually very close to the limit of rotational stability for the Earth. The main advantage of impacts accompanied by very high angular momenta is that they would release material predominantly from the proto-Earth rather than the impactor. But the disadvantage is that the high angular momentum and energy have to be syphoned off after the giant impact by a resonance involving Earth, Moon and Sun. At present it is unclear whether this mechanism can be invoked to remove the large amount of excess angular momentum that accompanies these alternative giant impact models.

Both measurements of lunar rock compositions and hydrodynamic models agree that the classic GIH, involving a Mars-sized impactor and a constant angular momentum, must be rejected. As summarised above, new impact-based hypotheses have been developed, but these require additional assumptions and a process to remove large amounts of angular momentum. Some alternative hypotheses that do not start with the premise that a giant impact caused the formation of the Moon have also been proposed. We developed a hypothesis in which the Moon is formed of terrestrial material at an angular momentum close to the present value. Our hypothesis [7] is based on the concentration of fissile material concentrated in the Core-Mantle Boundary (CMB) of the Earth by a mineral called calcium silicate perovskite. By natural concentration the fissile material gets concentrated and spontaneously leads to georeactors [8]. Triggered by a small impact or by natural concentration processes, concentration of fissile material in the georeactor causes the reactor to become supercritical leading to a nuclear explosion. This explosion produces a shock wave propagating towards the surface where it ejects iron-poor silicate material into space, from which the Moon eventually forms. The shock wave emission does not disturb the isotopic and elemental composition of terrestrial silicate rock material. The presence of georeactors has been shown to be feasible and simulations indicate that such a shock wave emission is realistic [8]. At present our hypothesis is at least as consistent with observations as the latest impact-based hypotheses.

At the moment, instead of being a done and dusted deal, the formation of our Moon remains shrouded in mystery. One reason for this may be that our present knowledge of the composition of the Moon is mainly based on the analysis of some of the 380 kg of samples collected at the Moon's surface from a small area on its near side. Future lunar missions that could bring more material

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especially from the lunar far side and originating at great depths in the Moon may yield a more complete picture of the composition of the Moon. Their analysis will yield more insight in the formation of our celestial companion. ■

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The authors respond

by J. Geiss, M.C.E. Huber, A.P. Rossi

We wrote our Feature to highlight the importance of lunar research for understanding the evolution of the Solar System as a whole, and not to critically assess hypotheses on the Moon's origin. Hence our premise "… a collision of the Earth with another planet – the Giant Impact – is the most widely accepted theory for the origin of the Moon."

However, given new experimental evidence, which permits a firm differentiation between giant-impact and geo-reactor hypotheses of lunar origin, we may now directly address the issue of falsification of models raised by the authors of the above text.

Solar-System bodies are heterogeneous in their isotope composition. So, if the Moon stems from a *collision* between Earth and another body, then Moon and Earth should have retained isotopic signatures of the two original bodies. If Earth and Moon have a *common origin*, such as a Moon arising from an Earth-bound explosion, one would expect them to have identical isotopic signatures.

While our EPN article was in press, Herwartz *et al.* (2014, *Science* **344**, 1146-1150) published compelling evidence that lunar rocks contain not only matter from the Earth: Herwartz *et al.* found a distinct isotopic difference between Moon and Earth. Comparing their results with predictions of model calculations they concluded: "our triple oxygen isotope data … supports the giant-impact hypothesis of Moon formation."

On the other hand, a hypothesis like the one promoted in the Letter to the Editor, which critically depends on a nuclear explosion in the Earth's interior, needs to explain the now established difference in the triple oxygen isotope composition between Earth and Moon, while being constrained by other observations. ■