MOON FORMATION

Earth's titanium twin

A giant impact on the young proto-Earth is thought to explain the formation of the Moon. High-precision analysis of titanium isotopes in lunar rocks suggests that the Moon and Earth's mantle are more similar than existing models permit.

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The Solar System is a wild place — isotopically speaking, at least. Meteorites show differences in isotopic compositions that can be much larger than those measured in terrestrial rocks. These differences are thought to derive from different admixtures of the most primitive known minerals — presolar grains — and the decay of short-lived radionuclides that existed in the first few million years of the Solar System. Titanium isotopes, as it turns out, are a good example of this effect. Writing in *Nature Geoscience*, Zhang and colleagues[1] report that, whereas all terrestrial rocks show identical $^{50}Ti/^{47}Ti$ ratios to within 0.0001%, some meteorites show deviations from the terrestrial ratio of up to 0.05%. More importantly, after correcting for cosmic radiation effects, they find that the Earth and Moon are geochemical twins in their titanium isotopes.

To many planetary scientists, that might come as a surprise. The favoured scenario to explain the formation of the Moon involves the collision of a Mars-sized proto-planet named Theia with a young proto-Earth[2]. This giant impact would have produced a disk of material orbiting the Earth, which would have condensed within centuries[3] and accreted rapidly thereafter[4] to form the Moon. Numerical simulations of the moon-forming impact have repeatedly shown that no more than about 60% of the material that ended up in the disk can have come from the Earth's mantle[2,5]; according to the models, the rest must be derived from the impactor. Theia — like all other known Solar System bodies — probably was geochemically distinct from the Earth's mantle. The isotopic composition of the Moon should therefore reflect a geochemical mix between Earth-like material and Theia-derived wilderness.

By contrast, Zhang *et al.*[1] find that the Earth and the Moon are identical in their titanium isotopic compositions within errors of 0.0004% — almost the limit of detectability. This is not the first time the giant impact hypothesis has been challenged by isotopes. During the past decade, similarities between lunar and terrestrial rocks have been identified for oxygen[6], silicon[7], chromium[8] and tungsten[9] isotopes. The latter three can be brought into accordance with the latest giant impact

Figure 1 | Earthrise as observed from the KAGUYA spacecraft in orbit around the Moon. Zhang *et al.*[1] show that the Moon is compositionally indistinguishable from the Earth's mantle in highly refractory titanium isotopes. This is inconsistent with numerical models of a moon-forming giant impact, which produce a Moon from a mixture of Earth and impactor material.

simulations[5], if one assumes that Theia had a composition similar to Mars — possibly the only surviving planetary embryo from which the larger terrestrial planets accreted[10]. However, the oxygen isotopic compositions of terrestrial and lunar rocks are so similar that, if Theia had a Mars-like composition, it cannot have contributed more than a few per cent of material to the Moon-forming disk[6]. Zhang *et al.* demonstrate that titanium isotopes are similarly constraining.

The simplest solution to this puzzle is to assume that the Moon formed almost exclusively from the Earth's mantle. But this is — thus far — not supported by numerical simulations. Alternatively, Theia could have been compositionally Earth-like. However, out of the known meteorite groups, only a few are sufficiently similar in oxygen isotopes. A volatile-rich, icy Theia from the outskirts of the Solar System is also excluded by the titanium isotopes, unless its rocky portion contributed less than 2% to the Moon-forming disk. Nevertheless, as Zhang *et al.* suggest, the scenario of an icy Theia is worth exploring in more detail.

If Theia was isotopically distinct from Earth, exchange of material between the Earth and the orbiting disk may have erased all remaining isotopic differences[3]. For a relatively volatile element like oxygen, such post-impact equilibration can be expected. But for a highly refractory element like titanium, equilibration is possible only if either the Moon-forming disk cooled exceptionally slowly[1], or if the large-scale turbulent mixing was unrealistically large[11].

Lunar formation models must explain a Moon that is geochemically more similar to the Earth's mantle, in both volatile and highly refractory elements, than can be explained by existing hydrodynamic impact simulations alone. This finding shifts the focus of future work on the giant impact towards the later part of the story: isotopic equilibration, cooling and turbulent mixing of the disk, as well as the final accretion of the Moon. Starting from the isotopic constraints determined by Zhang *et al.*[1], future studies will need to address whether the giant impact scenario can be revised or if alternative hypotheses are required to match the observations. ❐

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