

Alternative hypotheses for making the Moon

The article "Making the Moon" by Dave Stevenson (PHYSICS TODAY, November 2014, page 32) is an interesting one. It provides a nice summary of the history of that puzzle together with a clear explanation of the seemingly contradictory observations that must be reconciled in order for us to understand how the Moon was formed. And, as the article acknowledges, the puzzle remains as unsolved today as it ever was.

A paper by Edward Belbruno and J. Richard Gott III, which Stevenson did not cite, provides a truly compelling case for the low-energy, Mars-sized impactor scenario for the formation of the Moon.¹ Belbruno and Gott posit that a large body could have formed at one of the two stable Lagrange points (dubbed L4 and L5) that are co-orbital with Earth, grown to a substantial size, and eventually gotten kicked loose by interactions with other planetesimals. Thus that large body could have been put in a so-called horseshoe orbit in conjunction with Earth and eventually gotten perturbed to the point that it impacted Earth.

The scenario above makes it easy to reconcile the angular momentum, Earth-matching oxygen-isotope abundance, and lack of iron core in the Moon. Also, Lagrange and horseshoe orbits are common. Jupiter has large agglomerations of asteroids at its two stable Lagrange points. Saturn's moons Janus and Epimetheus are in a horseshoe orbit around the planet. And even Earth has an asteroid (AA29) in a horseshoe orbit with it.

The scenario put forward by Belbruno and Gott explains all the hard-to-reconcile observations.

Letters and commentary are encouraged and should be sent by email to ptletters@aip.org (using your surname as the Subject line), or by standard mail to Letters, PHYSICS TODAY, American Center for Physics, One Physics Ellipse, College Park, MD 20740-3842. Please include your name, work affiliation, mailing address, email address, and daytime phone number on your letter and attachments. You can also contact us online at <http://contact.physicstoday.org>. We reserve the right to edit submissions.

Reference

1. E. Belbruno, J. R. Gott III, *Astron. J.* **129**, 1724 (2005).

Robert Vanderbei
(rvdb@princeton.edu)
Princeton University
Princeton, New Jersey

■ **Dave Stevenson**, in his article "Making the Moon," suggests that the giant-impact hypothesis is an appealing one. I see some truth in that, yet it invokes a hypothetical Mars-like planet, "Theia," for which there is no current evidence.

Advocates of the giant-impact hypothesis also have to get around the problem that the Moon and Earth are isotopic twins having, to high precision, the same oxygen and titanium fingerprints. Theia is thought to have formed at roughly the same distance from the Sun as Earth did, but it is still likely to have had a different composition because of variations in solar system nebulae.

So the theory lacks a mechanism for the Moon and Earth to have identical isotopic compositions.¹ A novel equilibrium-of-oxygen-isotopes hypothesis has been proposed,² but the finding that titanium, which is highly refractive and would not easily equilibrate, also exhibits identical isotopic compositions is clearly a challenge for the giant-impact view.³

Numerical simulations can achieve Earth and Moon isotope compositions that are similar to each other, but currently only with proto-Earth spinning every 2.7 hours, close to the rotational instability limit. That spin period means the angular momentum of the Earth-Moon system would have been much higher before collision than today. "Evection resonance," described in Stevenson's article, was recently proposed to address the problem of having to remove excess angular momentum.⁴

In view of the current problems of the giant-impact hypothesis (contamination by Theia, problem of excess angular momentum, presence of lunar water), I propose an alternative hypothesis: explosive fission, in which the mantle of an initially fast-spinning proto-Earth is fragmented and the Moon is thrown off as a spinning cannonball. Explosive fission might explain the Moon's anomalously high orbital angular momentum.

The new Earth would recoil with explosive torque as the Moon took up a non-equatorial orbit.

In this scenario, the Moon is initially close to Earth and would be subject to strong tidal disruption—a potential problem, but total disruption is not necessarily a certainty. So in principle, survival of an ejected Moon into orbit cannot yet be ruled out.

Explosive fission requires no excess momentum. An explosion assumes no external torques and so conserves the vector angular momentum. Therefore, if proto-Earth had the same angular momentum as the current Earth-Moon system, it would have had a spin period of approximately four hours, well beyond the instability period. An explosion could also account for the change in Earth's axial tilt from its initial 9° to today's 23.4°.

Heterogeneous cold accretion is preferred since, by proto-Earth forming under low temperatures, water is retained along with the other metallic and nonmetallic volatiles in addition to the nonvolatiles. Proto-Earth's iron core could have been built at a low temperature from iron particles that collided and stuck.⁵ Gravitational differentiation and the explosion would provide an additional main heat source lacking in other cold-accretion models.

Explosive fission could have been fueled by the combustion of hydrogen released from water stored inside proto-Earth, but originally sourced from a cold solar-system nebula. This scenario is consistent with the presence of Earth's water (oceans and within the mantle) and the discovery of lunar water.

A mechanism is needed to split primordial water into the required hydrogen and oxygen. One mechanistic model for the hydrogen explosion is a spherical shell of water and other solar gas-cloud components trapped between proto-Earth's core and the overlying mantle. The mantle, in gravitational collapse, would have adiabatically compressed and heated the aqueous shell to effect the thermal decomposition of water (typically efficient at 3000–4000 °C) and the explosion that quickly followed.

The ignition and combustion of the hydrogen shell would have created a high-temperature and high-pressure