Alternative hypotheses for making the Moon

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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

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■ **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 nonequatorial 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 shock wave capable of cracking and fissioning off the explosion-modified mantle to form the Moon. An *in situ* Moon formed by self-gravitation would then be thrust through proto-Earth's surface, shattering the Moon surface to a certain depth and creating a temporary birth hole and signature effects on Earth. Such a violent lunar birth would also produce telltale explosive features on the Moon.

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■ **Stevenson replies:** I thank these letter writers for their alternative suggestions. Actually, neither is really new, and my failure to mention them—or others—is not because I was unaware of their existence, but rather because of the major challenges that these alternatives must overcome. In the Lagrange point scenario, which is widely known in the community, the challenge is to devise a story in which such bodies naturally arise in the context of a model that explains the planetary system, not just Earth–Moon. It is not sufficient to postulate them. A new paper[1] might suggest that the similarity of the impacting body and target is not so unreasonable. In the more astonishing fission story, the challenge lies in the basic physics of the proposed process, which is questionable.

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Notes on the history of the Coriolis effect

A colleague recently shared with me some back issues of PHYSICS TODAY. In one of them (August 2011, page 8), Christopher Graney wrote that the deflection of moving objects seen from within a rotating frame of reference was described by Giovanni Riccioli and Francesco Grimaldi in 1651, nearly two centuries before Gaspard-Gustave Coriolis obtained his celebrated theorem on relative motion. But it should be pointed out that Riccioli and Grimaldi were elaborating on an argument discussed by Galileo Galilei two decades earlier, in 1632: In the second day of his *Dialogue Concerning the Two Chief World Systems*, Galileo explains,

> In shooting the cannon, it and the target are moving with equal speed, both being carried by the motion of the terrestrial globe. Although the cannon will sometimes be placed closer to the pole than the target and its motion will consequently be somewhat the slower, being made along a smaller circle, this difference is insensible because of the small distance from the cannon to the mark.[1]

Thus, whereas Galileo argued that the deflection produced by a rotating Earth was too small to be observed, Riccioli and Grimaldi argued that the lack of observation was proof of a steady Earth.

Continuing the discussion, Manuel López-Mariscal (PHYSICS TODAY, November 2012, page 8) wrote that it is well known that Pierre Simon Laplace used the Coriolis force in his study of ocean tides in 1775. Earlier instances of the use of the Coriolis force are not so well known: Euler's equations governing the motion of a liquid in a rotating tube and Clairaut's equations governing the constrained motion of two masses in a plane.[2] None of those antecedents should, however, undermine the fact that Coriolis's theorem is one of the great achievements of classical mechanics.[3] Sometimes it is cursorily stated that Coriolis derived the force acting in a rotating system, but his theorem actually gives the complete transformation of the equations of motion for any moving frame. So, for example, Jean-Baptiste Bélanger used Coriolis's theorem to study the motion relative to a translating system:[4] For uniform motion, he found that the equations are the same as in a system at rest (Galilean invariance), whereas for accelerated motion, he found that a uniform force field has to be added to the equations[5] (equivalence principle).

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The roots of polaron theory

In his review of the book *Polarons* by David Emin (PHYSICS TODAY, October 2014, page 54), Jozef Devreese properly emphasizes the role of large polarons as both a general theoretical concept and a physical object. Polarons are electrons dressed by a cloud of virtual phonons in solids. To the best of our knowledge, they present the first example of propagating self-localized excitations in a quantum field theory. Devreese lists brilliant theorists who were inspired by the theory of polarons and significantly contributed to it, but he makes a serious omission when it comes to the roots of the polaron theory and the very origin of the term "polaron."

The general idea of electron trapping by a crystal lattice goes back to the seminal 1933 paper by Lev Landau.[1] That paper, which Devreese mentions, is primarily concerned with the resulting lattice defects, such as color centers in sodium chloride. Landau does not specify the trapping mechanism and contrasts a trapped electron with what he refers to as a freely moving electron.

The polaron was proposed, and the term coined, by Solomon Pekar. In two papers[2] published in 1946, he developed a self-consistent theory of a large polaron as a spontaneously trapped state of an electron strongly coupled to the induced polarization of atomic displacements in an ionic crystal. In his initial papers, Pekar considered polaron states to be "local," but in the follow-up papers[3] he identified polarons, rather than band electrons, as charge carriers in ionic crystals. That concept was developed and substantiated in a joint 1948 paper by Landau and Pekar in which they calculated the effective