Physics Today

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Citation: Physics Today **67**(11), 32 (2014); doi: 10.1063/PT.3.2583
View online: http://dx.doi.org/10.1063/PT.3.2583
View Table of Contents: http://scitation.aip.org/content/aip/magazine/physicstoday/67/11?ver=pdfcov
Published by the AIP Publishing

Making the MOON

David J. Stevenson

It's likely that our Moon emerged from a giant collision between Earth and a body the size of Mars. But getting that story, or any other, to fully square with the evidence has proven difficult.

Ancient philosophers imagined their world as made of earth, water, air, and fire. A fifth element, known as quintessence or ether, was thought to be incorruptible, beyond Earth, and thus included the Moon. That otherworldly vision isn't unique. Ideas and myths of old about the origin of our Moon often involved colorful stories in which the Moon was once on Earth—as the head of a goddess, perhaps—or part of Earth.

Modern stories can be just as striking but are not mere figments of the imagination; they are tested through physics and chemistry. Many are not yet settled—perhaps not even close to being settled—and that's what makes the subject of the Moon's origin so interesting. It is a long-standing puzzle that seems to become more difficult as new information is learned about the pieces. Like implementing fusion on Earth, an explanation for the origin of the Moon always seems to be a decade away. A standard idea envisioned in figure 1—a giant impact on Earth by a body roughly the mass of Mars—is compelling, but getting that story to explain all that we see has proven elusive.

This is forensic science: Planetary scientists at a crime scene—in this case, the aftermath of the Moon's formation—use the clues at hand to try to figure out what happened. Modern detectives often have to rely on DNA evidence to establish who did what, using other evidence, such as blood splatters, footprints, and broken glass, as diagnostics. Scientists are in a similar position, on the scene long after the events that took place; they examine chemical clues—especially isotopes, the natural analog of DNA for planets—and use physical reasoning to figure out what happened.

Why should we care? For one thing, the Moon has had profound effects on the history of Earth and quite likely on the evolution of life. And solving how we came to have our Moon may illuminate another question: why Venus has none. More generally, the formation of the Moon is a key piece in the puzzle of how our solar system evolved into the architecture we see. As scientists collect more information about planets around other stars, it will be fascinating to learn the frequency with which they have moons.

Lunar formation

Moons are common. All the planets in our solar system except for the innermost two, Mercury and Venus, have natural satellites. Many smaller bodies, including Pluto, have one or more moons. Although the details are uncertain, satellites naturally arise from the process for making planets, and planetary systems are an expected consequence of star formation. Indeed, we now suspect that most stars have planets. We don't yet know about moons around exoplanets.

The angular momentum of an interstellar cloud of gas and dust, collapsing under gravity, will lead to a star that has a disk. Within that disk, solid bodies called planetesimals, tens to hundreds of kilometers in radius, form quickly, within a million years. (See the article by Robin Canup, PHYSICS TODAY, April

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2004, page 56.)

We know that about our own solar system from the evidence for short-lived radionuclides and the dating of meteorites, debris from impacts between those early-forming planetesimals. The oldest meteorites are found to be about 4.568 billion years in age. We also have strong theoretical reasons to suspect that somewhat larger bodies—perhaps of a size the order of Earth's moon but up to and including the size of Mars—form quickly from the smaller planetesimals. Indeed, isotopic evidence suggests that Mars itself may have formed within a few million years. Building still bigger bodies requires the crossing of orbits, which most likely meant that those bodies were scattered by distant encounters with each other—a process that extended over tens of millions of years to even a hundred million years.[1]

In that picture, moons can arise by several processes:[2]

- Intact capture, whereby two bodies form a binary system during an encounter.
- Disruptive capture, whereby material is gravitationally caught and added to a disk or ring around a planet as small bodies collide with the ring. The Moon could then arise from accretion of the orbiting material.
- Fission, whereby the planet is spun up to a rotation rate such that the acceleration at the equator exceeds self-gravity.
- Giant impact, whereby a large impact leads to a circumplanetary disk that then coalesces to form a moon.

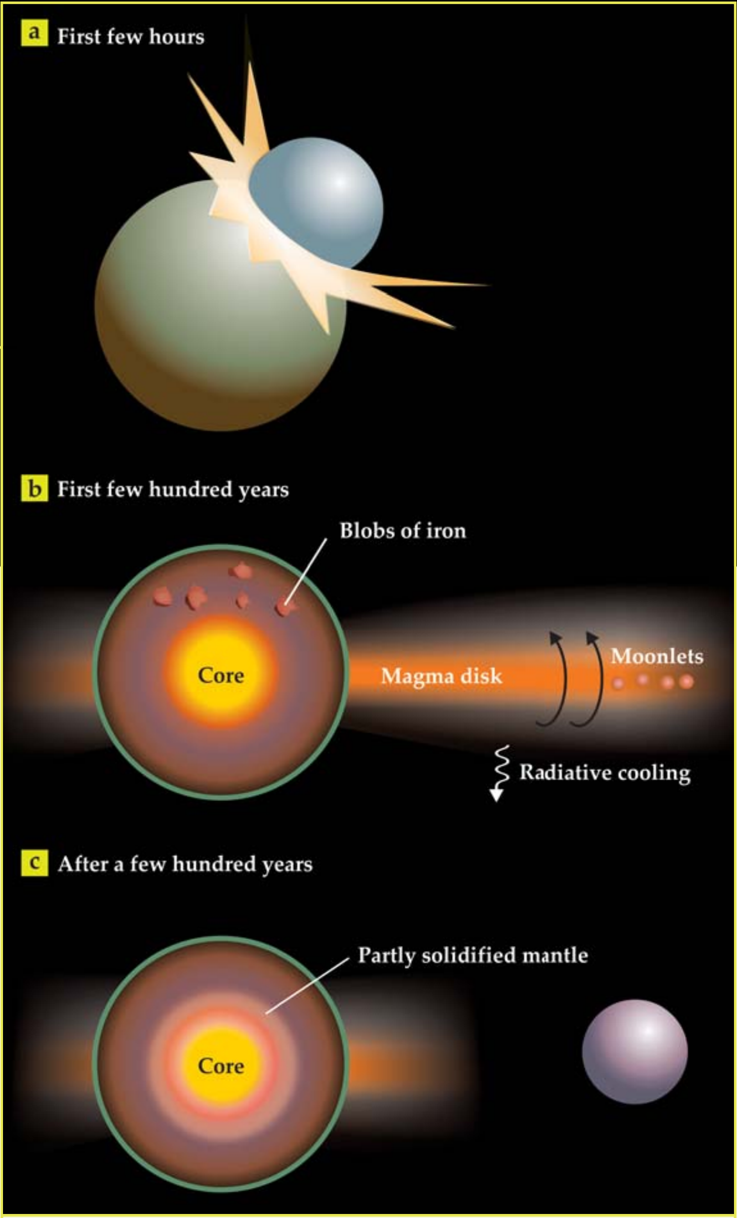


Figure 1. The giant-impact hypothesis. (a) A Mars-sized body hit Earth obliquely at a velocity not much higher than Earth's escape velocity, 11 km/s. Most of the impacting material merged with Earth in about 24 hours or less. **(b)** About 20% of the material ended up in close orbit and formed a magma disk of liquid and gas that spread, became well mixed, and cooled over hundreds of years. Roughly half of that disk went into making the Moon; the other half fell to Earth. Moonlets beyond the Roche limit—the distance within which self-gravitating bodies are ripped apart by tidal forces—aggregated into the Moon in about a thousand years or less. **(c)** Blobs of iron from the impact eventually settled into Earth's core, surrounded by a partially solidified mantle. A molten Moon formed just beyond 3 Earth radii and then rapidly receded, driven outward by the tides it raises in Earth. The Moon now orbits at 60 Earth radii. (Adapted from ref. 12.)

Box 1. The green-cheese theory of the Moon

The myth that the Moon is made of green cheese—where "green" refers not to color but age—supposedly comes from stories in which a simpleton sees a reflection of the Moon in water and mistakes it for a round cheese wheel. In the spirit of modern science, Edward Schreiber and Orson Anderson tested the green-cheese hypothesis in 1970 by comparing the seismic, or sound-wave, velocities of rocks returned from the Moon with the measured sound speeds in cheese.[15] Seismic velocities are often used in Earth science to infer rock composition, thanks to the strong correlation of sound speed with density. Some of the values Schreiber and Anderson reported are shown here.

According to the data, the Moon is far better described by cheese (green or otherwise) than by terrestrial rock. The explanation for so absurd a result lies in the fact that the lunar near surface, which includes the rocks collected by the Apollo astronauts, has been repeatedly broken up and partially sintered back together during the Moon's long history of asteroid bombardment. The bulk density of lunar materials is much higher than typical cheeses, but because of the bombardment, rocks in the Moon's outermost 1-km layer are highly porous, which accounts for their abnormally low sound speeds. The comparison between lunar and terrestrial rocks is thus a reminder of the danger of reaching conclusions from limited measurements.

	Seismic velocities (km/s)
Cheeses	
Sapsago (Switzerland)	2.12
Romano (Italy)	1.74
Cheddar (Vermont)	1.72
Muenster (Wisconsin)	1.57
Lunar rocks	
Basalt 10017	1.84
Basalt 10046	1.25
Near-surface layer	1.20
Terrestrial rocks	
Granite	5.90
Gneiss	4.90
Basalt	5.80
Sandstone	4.90

Intact capture is not possible in strictly two-body problems with no dissipation of energy. Given a third body or sufficient dissipation—for example, tidal effects or the presence of debris or gas—intact capture does become possible. The retrograde inclined orbit of Triton about Neptune may have arisen in that way.

Disruptive capture may work for making a small satellite, but the process has an angular-momentum difficulty: In the reference frame of the growing planet, large planetesimals arrive with little preference in the sign of their angular momentum. So the moon being built in such a process will have little net angular momentum given to it by accumulating bodies and will spiral into the planet and crash.

Fission was proposed for our Moon by George Darwin,[3] son of Charles Darwin, and some of the ideas now under consideration by planetary scientists are fission in a new guise. Darwin thought the Moon might have come from the region now filled by the Pacific Ocean. At least in diameter, it fits. Of course, we now know that the Pacific Ocean is a modern geologic feature, arising from plate tectonics. Fission has usually been dismissed on the stronger basis that the angular momentum of the Earth–Moon system is more than a factor of two smaller than that needed for the combined body to lose material at the equator.

The giant-impact hypothesis is appealing for two reasons. First, moons can naturally form when a planet does; indeed, they are a predicted feature of current models for building solid planets.[1] Second, the giant-impact hypothesis offers a natural explanation for the angular momentum of the Earth–Moon system. Currently, Earth's rotation has only 20% of the angular momentum of the Earth–Moon system. The rest is in lunar orbital motion.

The current orbital angular momentum of the Moon is readily estimated to be about $M_M(60GM_ER)^{1/2}$, where G is Newton's gravitational constant, M_M is the mass of the Moon, M_E and R are the mass and radius of Earth, and $60R$ is the current distance of the Moon from Earth. Because $M_M \approx 0.012M_E$, the total angular momentum of the Earth–Moon system is currently about $0.12M_E(GM_ER)^{1/2}$. Consider a Mars-sized mass about 10% of Earth's mass falling into Earth's gravity field such that it hits Earth at around the escape velocity and does so obliquely with an impact parameter about equal to Earth's radius. The total angular momentum provided by the impact is then approximately $0.1M_E(2GM_ER)^{1/2}$, about equal to what's required. The angular momentum of the Earth–Moon system is usually assumed to be roughly conserved over time because solar tides are small, so the simple calculation supports the idea of deriving the observed angular momentum from a singular giant impact.

The appeal of a giant-impact origin was recognized in the mid 1970s, independently by two teams, William Hartmann and Donald Davis,[4] who published first, and Alistair Cameron and William Ward.[5] But it was not until the mid 1980s that geoscientists used numerical simulations to demonstrate that such an impact would put the desired amount of material into near-Earth orbit.[6] The actual impact happens on a time scale of hours, large amounts of melting and even vaporization of rock ensue, and some material—the equivalent of about 20% of the projectile mass—has sufficient angular momentum to end up in orbit. The Moon would then accrete quickly, in hundreds to thousands of years, and move outward under the action of tides to its present location.

Figure 1 shows the standard scenario. Although not all aspects of the picture are well understood, the physics is supported by detailed modeling. Indeed, simulations can get roughly the right moon mass and the right total angular momentum, the two most important physical constraints. However, the argument for a giant impact comes from considering more than just the dynamics.

The nature of our Moon

The natural first step in understanding our Moon is to consider its composition. We've all heard the amusing myth that the Moon is made of green cheese, a theory that, astonishingly, has been tested (see box 1). The six Apollo Moon missions, conducted between 1969 and 1972, now seem like ancient history in the context of planetary exploration, but the Moon remains the only body from which we have returned samples. The analysis of those rocks continues to be a lively area of science because of the dramatic improvement in precision analysis—both in the accuracy of standard techniques and in the development of new techniques and new isotopic systems. Scientists also get rocks from elsewhere in the solar system as meteorites, and although their provenance and history is uncertain, such rocks provide a context for assessing Earth and the Moon.

The emerging conclusion is that the Moon is in many ways like a piece of Earth's mantle, though dusted off—that is, with some volatile elements removed. Indeed, if one could construct a fission story that was physically acceptable, it might earn acclaim as the most plausible explanation. Absent that, we seek a giant-impact model that allows the Moon-forming material to come mostly from Earth or allows the projectile to be remarkably similar to Earth. The non-giant-impact alternatives for explaining the Moon are not only dynamically unsatisfying but provide no natural explanation for the remarkable similarity of Earth's mantle and the Moon.

To claim that the Moon is almost indistinguishable from a piece of Earth, we need a standard by which to measure the similarity. Bulk composition won't do, for by that measure Earth and the Moon differ substantially in the amount of metallic iron: Earth contains a large metal core, whereas the Moon's core is proportionately tiny. Nor can we use the crustal Moon rocks for the comparison: The crust in the ancient lunar highlands is a distinctive byproduct of an early hot history that allowed mineral-rich crystals known as anorthosite to float near the surface. Those measures reveal more about the processes that took place when the bodies formed and little about the source location of material used to make them. For that we must turn to isotopes.

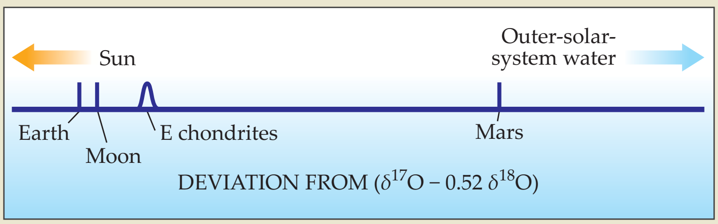
The value of isotopic measurements lies in the likelihood that some carefully chosen isotopic signatures tell us about reservoirs rather than process. Oxygen, with its three stable isotopes, is particularly useful in identifying material differences that cannot arise from physical or chemical processes, as outlined in box 2. Those differences were presumably set up when the solar system formed and then were preserved through time, which makes it possible, for instance, to identify material that comes from Mars, irrespective of the material's geological evolution.

That oxygen signature, denoted by Δ, is shared by everything on Earth, apparently without significant exception. The oxygen in your body has the same Δ as a randomly chosen rock (excepting meteorites) or piece of ice from anywhere on Earth. Were there recent Martian immigrants in our midst, by contrast, the distinctiveness of their oxygen isotopes would be a convenient way to identify them. Remarkably, the difference in Δ between Mars and Earth is 20 to 30 times larger than the difference between the Moon and Earth.[7] Some solar-system reservoirs are much more different still. For example, the Sun–Earth difference in Δ is more than an order of magnitude larger than the Earth–Mars difference.

It is reasonable to suppose that there was a gradient in Δ throughout the region from which terrestrial planets formed. It is also reasonable that Earth is not likely to have formed from material that was initially confined to a narrow zone, because there would not be enough mass. Indeed, the isotopic evidence for Earth's formation suggests that it took tens

Box 2. Oxygen isotopes

Oxygen has three stable isotopes, of mass 16 (the most common), 17 (the least common), and 18. The procedure for describing the isotopic oxygen signature of any material is to choose a standard—Earth's ocean water, typically—measure the material's ratios of ^{18}O to ^{16}O and ^{17}O to ^{16}O, and compare them with the standard. The result is expressed in delta notation; for example, $\delta^{18}O$ refers to the extent to which the ratio of ^{18}O to ^{16}O differs from the standard. The main trend of all solar-system oxygen isotopic measurements lies close to the line $\delta^{17}O = \delta^{18}O$—and is believed to represent a mixing of a solar component from the Sun found in the solar wind (about −60 parts per thousand relative to Earth) and a water component found in some meteorites (+180 parts per thousand relative to Earth).[16]



Because there are three oxygen isotopes, it is possible to disentangle two trends—one leading to the line of slope one and the other due to common physical and chemical processes such as condensation and diffusion. We can identify a measurement of the material—denoted Δ and defined as $\delta^{17}O - 0.52\delta^{18}O$—that is unaffected by those standard processes. The fundamental origin of differences in Δ is uncertain but is believed to require very low density conditions and UV radiation. Thus Δ remains constant during planetary assemblage, except for the mixing of different reservoirs, and is believed to be indicative of provenance, not process.

The Earth–Mars difference in Δ is 300 times smaller than the difference between Earth and the Sun; the Earth–Moon difference in Δ is smaller still by an additional factor of about 25, as illustrated in the line graph.[7] Some meteorites, known as enstatite (E) chondrites, contain a spread of Δ values that are closer to Earth than materials used to make Mars. The smallness of the Earth–Moon difference is found not just among oxygen isotopes; multiple isotopic systems bear out the result.

of millions of years—possibly as much as a hundred million years—consistent with the time needed to bring together material over a substantial range of distances from the Sun. Accordingly, the body that hit Earth to make the Moon should have been isotopically different from Earth—possibly by an amount similar to the Earth–Mars difference.

However, the usually envisaged standard giant impact—the kind that explains the observed angular momentum—is known from numerical simulations to produce a disk primarily made from material in the impacting body. That's hardly surprising; the material that ends up in the disk is naturally the material with the largest specific angular momentum. Because both projectile and target would have each had a separated core and mantle at the time of their collision, the disk that emerged would have been mostly devoid of metallic iron. That explains why the Moon has a tiny core. But it leaves unexplained the very small difference in isotopic composition between Earth and the Moon.

Their compositional similarity extends to other isotopic systems, such as tungsten derived from the decay of hafnium. Unlike oxygen, hafnium can serve as a chronometer. One of its isotopes decays with a half-life of 9 million years to the tungsten isotope ^{182}W. Importantly, tungsten is a siderophilic ("iron-loving") element that is extracted from the mantle when a planetesimal or larger body differentiates to form an iron core. A small amount is left in the mantle if some core formation occurred late in the planet-building process, as was the case for Earth.

The observed similarity of Earth and the Moon in tungsten isotope ratios imposes constraints on the timing and nature of core formation in addition to constraints on the nature of the materials used to make Earth and the Moon.[8]

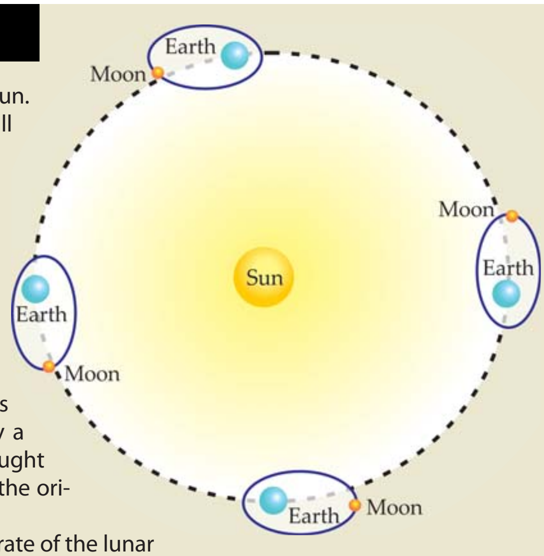
Imagined giant impacts

What could explain the remarkable similarity of Earth and the Moon? Three possibilities stand out:

Homogenization before formation. The process of planet building may have sufficiently stirred up the reservoirs of material in the vicinity of Earth's orbit such that everything that formed in that zone had about the same Δ. In that explanation, Mars was not part of the mixing process but an outlier, a spectator of the mayhem that took place in the zone internal to its orbit. That idea gains support from Mars's small mass and its inferred rapid formation time. The required homogenization has been neither excluded nor supported by any current model. And it is unclear whether homogenization will explain all of the isotopic systematics; tungsten presents a particular challenge.

Homogenization during formation. Although the disk produced by a giant impact is likely dominated by impactor material, Earth and disk material could still mix together during the hundreds of years before the Moon actually formed. The turbulent process would be analogous to what happens in a kitchen as several different dishes are being prepared: You smell a blend of all the vapors given off. It is unclear whether the blending is efficient enough to explain the very small difference between Earth and the Moon. In particular, Earth's deep interior may not have had the opportunity to equilibrate iso-

Box 3. The evection resonance



The Earth–Moon system is not isolated; it orbits the Sun. The separation between Earth and the Moon is small enough that the Sun is expected to be a minor disturbance, especially early in solar-system history when their separation was much smaller than it is today. However, even a small disturbance can have a big effect if a resonance exists. Because Earth spins, it is oblate; the flattening was more pronounced early in its history when Earth spun more rapidly and a day may have spanned just 5 hours. The gravity field experienced by the Moon is therefore not that of a point mass but includes a higher-order (quadrupole) term. As a consequence, the orbit of the Moon is not precisely a closed ellipse. The slight nonclosure of orbits can be thought of as the precession of the ellipse—each orbit rotates the orientation of the ellipse as viewed from an inertial frame.

The evection resonance arises when the precession rate of the lunar orbit matches the rate of Earth's orbital motion around the Sun (see the figure). It is certain that the resonance was encountered as the Moon spiraled outward from Earth under the action of tides. For the resonance to lead to a large extraction of angular momentum from the Earth–Moon system, however, it must also produce a sustained increase in the eccentricity of the lunar orbit. And that eccentricity increase may only happen for a particular, and not necessarily guaranteed, range of tidal parameters that describe the dissipation of tidal energy within each body. The angular momentum is transferred from the Earth–Moon system to the orbital angular momentum of Earth, which is so large that the change has no discernible effect on Earth's orbit.

topically with the disk in so short a time scale, and we have no evidence yet that the deep interior is substantially different from Earth's near surface in oxygen isotopes.

Formation directly from Earth. To get a circumplanetary disk that is derived mostly from Earth, it seems necessary to have an impact that violates the angular-momentum constraint. Planetary scientists have suggested two possibilities. One is to hit an Earth that is already close to fission with a fast-moving projectile. That could be thought of as impact-triggered fission. Another possibility is for the collision to happen between two "sub-Earths," two bodies each about half an Earth mass.

Figure 2 presents hydrodynamic snapshots of three kinds of giant impacts. Only the first—the standard giant impact of a smaller body colliding with Earth—satisfies the angular-momentum constraint.[9] But the other impact scenarios show how the material used to make the Moon can come mainly from Earth; for them to be candidates, one must find a way of getting rid of excess angular momentum. One method for doing so, proposed by Matija Ćuk and Sarah Stewart two years ago,[10] is an evection resonance, in which the precession rate of the Moon's orbit matches Earth's mean motion about the Sun (see box 3). Although the resonance is well known, its application to account for a loss of angular momentum is new.

At present, no one knows the answer to the formation puzzle. It could be a combination of all three possibilities or something else entirely. In the case of the evection resonance idea, which researchers are still analyzing, at issue is not the existence of the resonance but rather the need to have it in place for an extended period of time during which the eccentricity of the lunar orbit is large. That appears to require a particular and possibly narrow range of parameters for the tidal behaviors of Earth and the Moon.

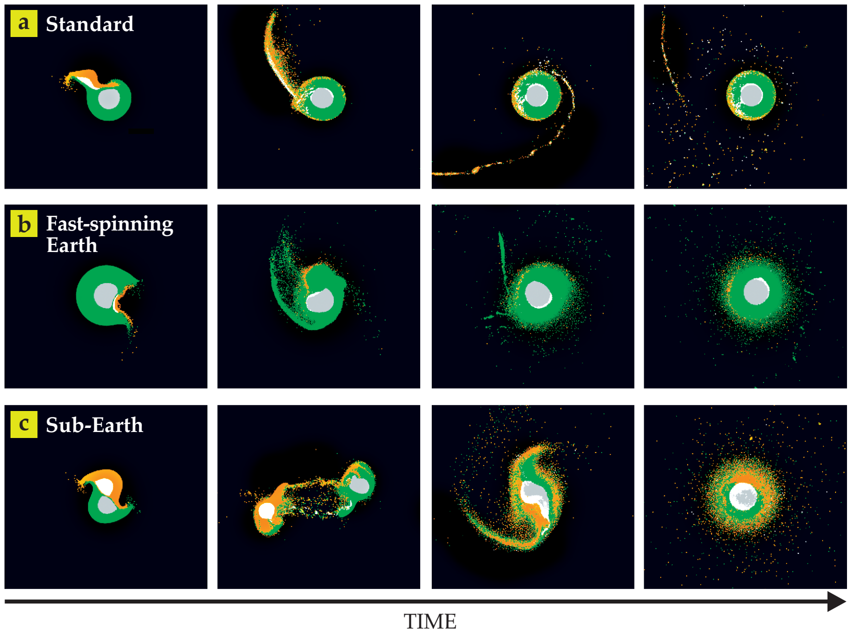


Figure 2. Hydrodynamic snapshots of giant impacts that might have been. In each of three cases, a projectile, whose mantle and core are shown in orange and white, respectively, obliquely hits Earth, whose mantle and core are shown in green and gray. Earth's North Pole points out of the page. The aftermath of each collision, projected onto the equatorial plane, is pictured from left to right, with several hours elapsing between each snapshot. **(a)** In the standard scenario,[9] the angular momentum of the impact equals that of the current Earth–Moon system, but the material that ends up in orbit is mainly projectile orange, a result at odds with the nearly identical isotopic ratios of oxygen, silicon, tungsten, and titanium observed in the real Earth and Moon. In the two other cases, **(b)** a small projectile smashes into a rapidly rotating planet,[10] and **(c)** two bodies collide, each with half of Earth's mass.[13] In all three cases, very little metallic iron ends up in orbit, a result borne out by observation. But only in panels b and c does primarily Earth's mantle (green) end up in orbit. For videos of the simulations, see the online version of this article. (Figure prepared by Miki Nakajima and adapted from results in ref. 14.)

What about Venus?

In 1672 Giovanni Cassini "discovered" the moon of Venus. Astronomers of the time thought it was obvious that Venus should have a moon because Earth was so endowed. The moon was named Neith, after an Egyptian goddess. Cassini's observation was "confirmed" by many others, and the orbit of Neith was confirmed by Joseph Lagrange in 1761. That same year, French mathematician Jean le Rond d'Alembert lamented to Voltaire in a letter, "I do not know what has happened with the lackey of Venus. I am afraid it cannot be a hired lackey which has ceased to stay with her for a long time, but rather that the said lackey has declined to follow his mistress during her passage over the Sun." It gradually became apparent that Neith was a false discovery.[11]

Planetary scientists no longer think that a moon of Venus should be obvious. Nor do they seek to understand Earth and the Moon in isolation but as part of a broader picture. Although Venus is closer than Earth to the Sun, an Earth–Moon system placed in the orbit of Venus would be stable for the age of the solar system. A stable moon for Mercury is far more difficult to imagine because of both the planet's low mass and greater proximity to the Sun.

Notwithstanding Mercury, the absence of a moon for Venus is puzzling considering that moons are thought to be readily made by giant impact. One possibility is simply to appeal to chance. Not all giant impacts lead to moons, and perhaps Venus lacked such an event. The alternative is to suppose that Venus once had a moon but lost it. The giant impact that made Earth's moon was very late, the last major event in the evolution of the inner solar system, according to isotopic evidence.

Had Venus formed a moon at an earlier epoch, the system could have been disrupted by close encounters with other large, still wandering planetary bodies. During that period, tides due to the pull of its moon would have reduced the spin of Venus and prepared it for a later evolution in which it was despun by solar tides to its current very slow retrograde spin. If that story actually happened, then the primary difference between Earth and Venus lies in timing.

Resolving the puzzle

Planetary science, including the study of lunar evolution, is being advanced in three ways: analytical laboratory measurements, simulations, and exploration. Analyses of rocks continue to be remarkably fruitful, in large part because of the startling improvement in measurement precision since the Apollo program. Numerical simulation has blossomed, though it still has some major technical hurdles; to some extent they can be met by a combination of laboratory experiments—using shock waves, for instance—and theoretical work.

The period of history a few hundred years after the giant impact, during which the protolunar disk cooled, spread, and allowed the Moon to coalesce beyond the Roche limit—the distance within which it is ripped apart by Earth's tides—remains murky. To better understand it, exploration remains crucial; NASA's GRAIL (Gravity Recovery and Interior Laboratory) mission, for example, in which two spacecraft flying in tandem around the Moon mapped its local gravitational fields, has provided valuable insights (see PHYSICS TODAY, January 2014, page 14).

To those three ways, one must add a cautionary caveat: It is possible that the most important next step is a clever idea or some change in our thinking about how Earth and our solar system formed.

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