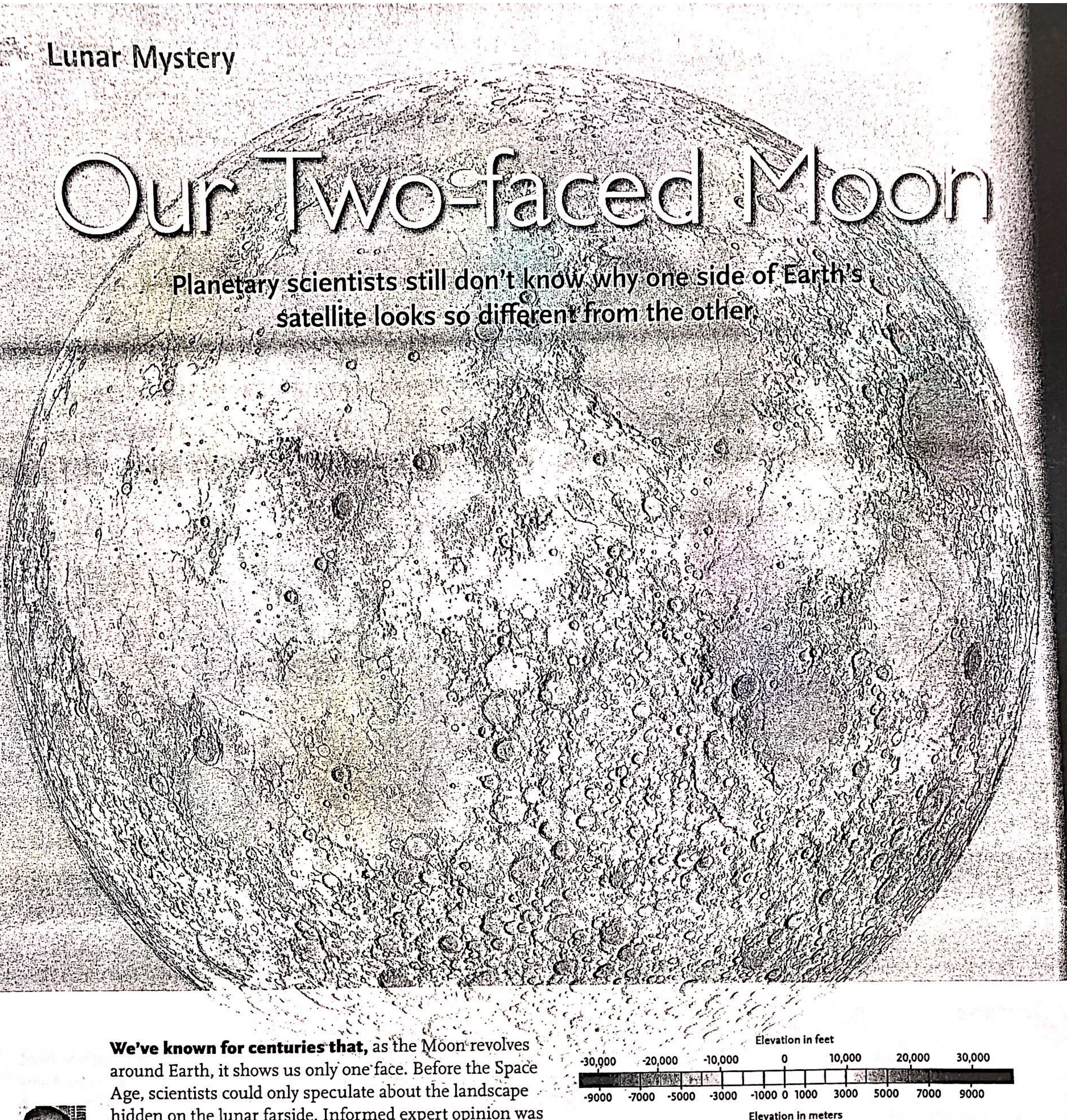
Our Two-faced Moon

Planetary scientists still don't know why one side of Earth's satellite looks so different from the other.

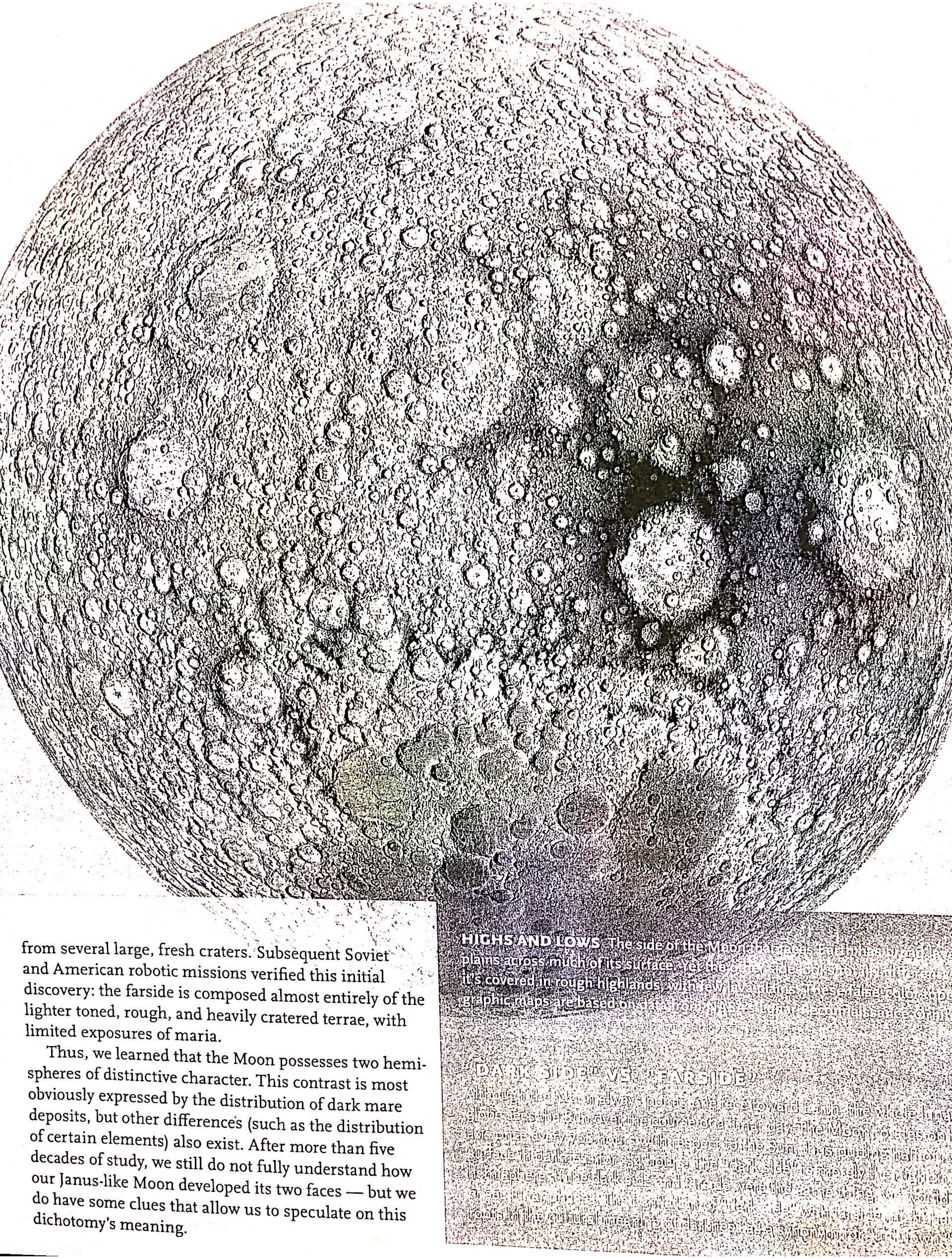


Paul D. Spudis

We've known for centuries that, as the Moon revolves around Earth, it shows us only one face. Before the Space Age, scientists could only speculate about the landscape hidden on the lunar farside. Informed expert opinion was that the farside probably looked similar to the nearside, with extensive low, smooth *maria* (Latin for "seas") set in rough, undulating highlands (*terrae*).

With the advent of spaceflight in the late 1950s, we finally saw the farside. That momentous event first occurred in 1959 thanks to the photographs captured by Luna 3, an automated satellite sent to the Moon by the Soviet Union.

Those first farside pictures were of poor quality and low resolution, but planetary scientists immediately realized that the near- and farsides are fundamentally different. The farside as seen from Luna 3 didn't show many of the dark maria (familiar to even the casual viewer) that are so widespread on the nearside. Except for a couple of small mare patches — including one patriotically dubbed "Sea of Moscow" by Soviet scientists and a dark, mare-filled crater named after rocket pioneer Konstantin Tsiolkovskiy — the farside appeared to be made up of mostly bright, rugged highlands, crisscrossed with rays



from several large, fresh craters. Subsequent Soviet and American robotic missions verified this initial discovery: the farside is composed almost entirely of the lighter toned, rough, and heavily cratered terrae, with limited exposures of maria.

Thus, we learned that the Moon possesses two hemispheres of distinctive character. This contrast is most obviously expressed by the distribution of dark mare deposits, but other differences (such as the distribution of certain elements) also exist. After more than five decades of study, we still do not fully understand how our Janus-like Moon developed its two faces — but we do have some clues that allow us to speculate on this dichotomy's meaning.

HIGHS AND LOWS The side of the Moon that faces Earth has bro [illegible] plains across much of its surface. Yet the other side looks totally different: it's covered in rough highlands, with few lava plains. These false-color topographic maps are based on data from NASA's Lunar Reconnaissance Orbi [illegible]

"DARK SIDE" VS. "FARSIDE"

Although the Moon always points one face toward Earth, the whole lunar globe sees the Sun over the course of a lunar day. The Moon rotates on [illegible] axis once every 708 hours with respect to the Sun, thus putting half of [illegible] surface in darkness for 354 hours. The "dark side" is merely the nighttime hemisphere; [illegible] dark side and farside [illegible] the same thing [illegible] a [illegible] phrase. The [illegible] "dark side" with farside [illegible] roots in the cultural meaning of darkness as a synonym for unknown [illegible]

The Lunar Maria

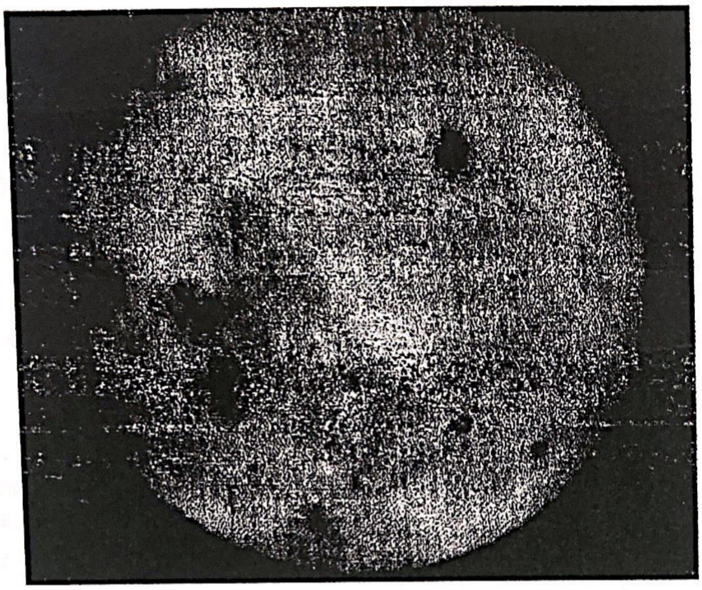
The Apollo explorations gave us a good understanding of the Moon's early history and evolution. We confirmed that the maria consist of ancient lava flows, which erupted onto the surface more than 3 billion years ago. These lavas arose when heat from the decay of radioactive elements deep within the Moon partially melted its magnesium- and iron-rich mantle, producing liquid rock that migrated upward toward the surface. This magma then erupted to form large deposits, similar to the massive sheets of lava that make up the Columbia River basalts in the western United States. Such eruptions can involve enormous volumes of magma and are called *flood basalts.*

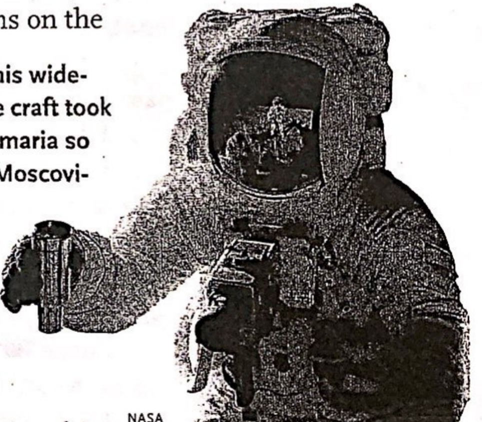
On the Moon, flood basalts fill gigantic impact features called basins. (By convention, planetary scientists define impact craters as basins when they are at least 300 kilometers across.) Some of these features are more than 1,000 km in diameter, as large as the state of Texas. The basins formed when asteroid-size bodies hit the Moon around 4 billion years ago, excavating large parts of crust and throwing ejecta across the surrounding highlands.

Basins create low areas and fractures in the crust. These fractures later allowed magmas to break through the surface and erupt onto it. The basins' low-lying interiors permitted these lavas to accumulate into stacks, pressing down on the crust and deforming the surface.

The infill of basins by mare lava is not a direct consequence of the impact. Instead, a significant length of time (hundreds of millions of years) usually elapsed between a basin's formation and its infilling by magma erupting from the deep interior.

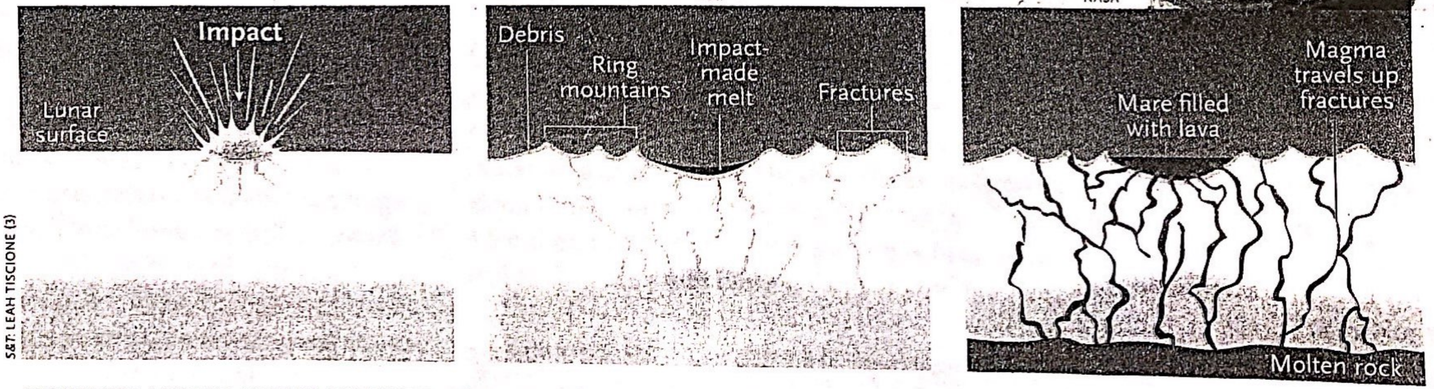
We have found impact craters and basins over the entire lunar surface, but not all basins are filled with lava — some are only partially covered, or not flooded at all. This is a critical point to note for understanding the origin of the hemispheric differences on the Moon: the abundance of maria on the nearside and their scarcity on the farside is *not* merely because there are fewer basins on the





NASA

FIRST LOOK AT THE FARSIDE *Above:* In 1959, the Soviet spacecraft Luna 3 captured this wide-angle shot of the lunar farside. Although of poor resolution, this image and the other 28 the craft took revealed that the Moon's farside (the right three-quarters of the disk seen above) lacks the maria so familiar to observers from the nearside. In the image, the dark spot at upper right is Mare Moscoviense; the one lowest on the center left is Mare Smythii. The small dark circle at lower right with the lighter dot in the center is the crater Tsiolkovskiy and its central peak. *Right:* Apollo 12 astronaut Alan Bean holds a container filled with lunar soil. (Crewmember Pete Conrad, who took this image on November 20, 1969, is reflected in Bean's visor.) Samples gathered by Apollo astronauts revolutionized the study of lunar geochemistry, and planetary scientists still use these samples to study the Moon's geologic history.



S&T: LEAH TISCIONE (3)

HOW THE LUNAR MARIA FORMED The Moon's lava seas formed in a multi-step process that spanned about a billion years. First, sometime between about 3.9 and 4.3 billion years ago, an asteroid slams into the surface, blasting out a basin even as the projectile is vaporized. The impact's shock waves fracture the underlying rock (left). The blast hurls debris into rings around the basin, while a small pool of shock-melted rock solidifies inside. Meanwhile, the rock beneath the basin rebounds upward, creating more cracks (middle). Much later — about 3.1 to 3.9 billion years ago — material heated and melted deep inside the Moon by radioactivity rises along the fractures as magma. When it reaches the surface, the lava fills the basin layer by layer to form a dark mare (right).

arside. In fact, basins are (more or less) equally distributed over both near- and farsides. Some other factor must have caused the volcanic flooding of almost all the nearside basins and only a very few of the farside ones.

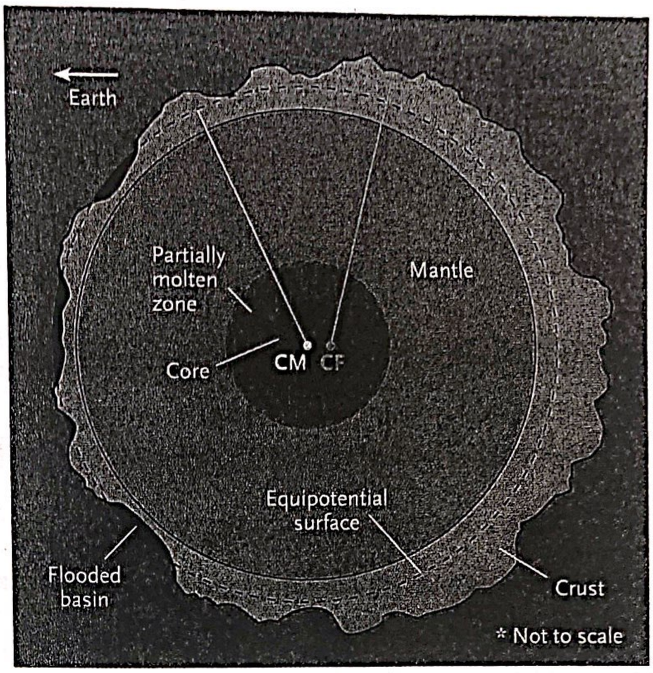
The Crust of the Moon

The lunar crust consists of aluminum- and calcium-rich rocks, similar to the terrestrial rock anorthosite. Anorthosite is made up almost entirely of one mineral: plagioclase, which has a relatively low density. Small rocks rich in plagioclase were first found in samples returned by Apollo 11. From this evidence and from looking at the highlands' topography and density, scientists concluded that the early Moon must have been nearly totally molten, covered by an ocean of magma in which low-density minerals floated to the top (forming an anorthositic crust) while denser, iron-rich minerals such as olivine sank to the bottom, ultimately becoming the mantle. It was this mantle that later partly remelted, through the slow release of heat by radioactive elements, to create the magmas that erupted as mare basalts.

The astronauts deployed long-lived instruments on the lunar surface, including seismometers that measured moonquakes. Study of these quakes showed that the Moon has a crust, a mantle, and possibly even a small metallic core. The lunar crust at the Apollo landing sites is between 35 and 40 km thick, similar to parts of Earth's continental crust. Interestingly, gravity data from orbiting spacecraft show that the crust on the farside is thicker than on the nearside, for reasons that remain unclear. In addition, the Moon's center of mass is offset from its geometric center by a couple of kilometers in the direction of Earth. This offset is probably what keeps the nearside visible and the farside facing away, because it would have forced the Moon's rotation and revolution periods to synchronize.

Armed with these findings, lunar scientists sought to explain the two faces' geologic differences. They first postulated that the difference in crustal thickness between the two hemispheres might explain why there are far more maria on the nearside. How would such a scenario work?

As mentioned, basalts are produced from the partial melting of the deep lunar mantle, forming bodies of liquid rock that are less dense than their surroundings and, therefore, buoyant. These liquids migrate upward along grain boundaries and cracks until they reach a point where they either escape to the surface and erupt or stop moving because the pressure from the overlying rock is no longer high enough to make them buoyant. Assuming all mare basalts came from the same "zone" of melting, scientists suggested that, because the crust is thinner on the nearside, the magmas could reach the surface there and erupt, but rising the same distance on the farside would still leave them below ground level.



S&T: GREGG DINDERMAN, SOURCE: SUSAN PULLAN / GEOLOGICAL SURVEY CANADA

LUNAR INTERIOR The Moon's *center of mass* (CM) is offset from its geometric center (called the *center of figure*, CF) by about 2 km toward Earth. This offset led to the gravitational lockup that keeps the lunar nearside facing our planet.

This explanation was attractive for a lot of reasons, especially as it unified several disparate observations into a generalized model that nicely explained a lunar mystery. But experience in science shows us that grand unifying theories are usually wrong — or, at best, incomplete. In this case, continued studies of the lunar samples returned by the Apollo missions demolished this *density equilibrium* idea. The composition of the liquid rock that filled maria changes from region to region, which means that the magmas' densities were different. That implies that, even *if* material all came from the same depth (unlikely), it wouldn't necessarily have risen the same distance. Thus, the contrast in the number of near- and farside maria can't merely be the result of magmas of similar densities rising to similar levels.

Lunar Heat

All the rocky planets contain radioactive elements that spontaneously decay into other elements, releasing radiation and generating heat. A classic example is the element uranium, half of which decays into lead over 4.5 billion years. Radioactive decay has been occurring inside the planets since they formed, and the heat that

A THIN VENEER

Although they can span hundreds of kilometers, maria are typically only a few hundred meters thick or less. They're usually thickest near basins' centers — sometimes reaching 2 to 4 km deep — and thinnest near the edges.

is generated partially melts the planets' interiors. The result is the generation of magma, which can cool slowly deep inside a planetary crust (a process called *plutonism*) or be rapidly pushed out onto its surface (volcanism).

Many different radioactive elements produce heat inside both Earth and the Moon. These elements are too large to fit into the crystal structures of the major rock-forming minerals. So as minerals crystallize from the magma, such elements tend to be left behind in the magmatic liquid that remains. On the Moon, this material has been given the name KREEP, which stands for potassium (K), rare-earth elements (REE), and phosphorus (P). We first discovered KREEP in Apollo 12 samples collected in Oceanus Procellarum, the largest expanse of maria. Because KREEP includes the radioactive, heat-producing elements uranium and thorium, a map of high radioactivity on the lunar surface is also a map of the KREEP content of different regions.

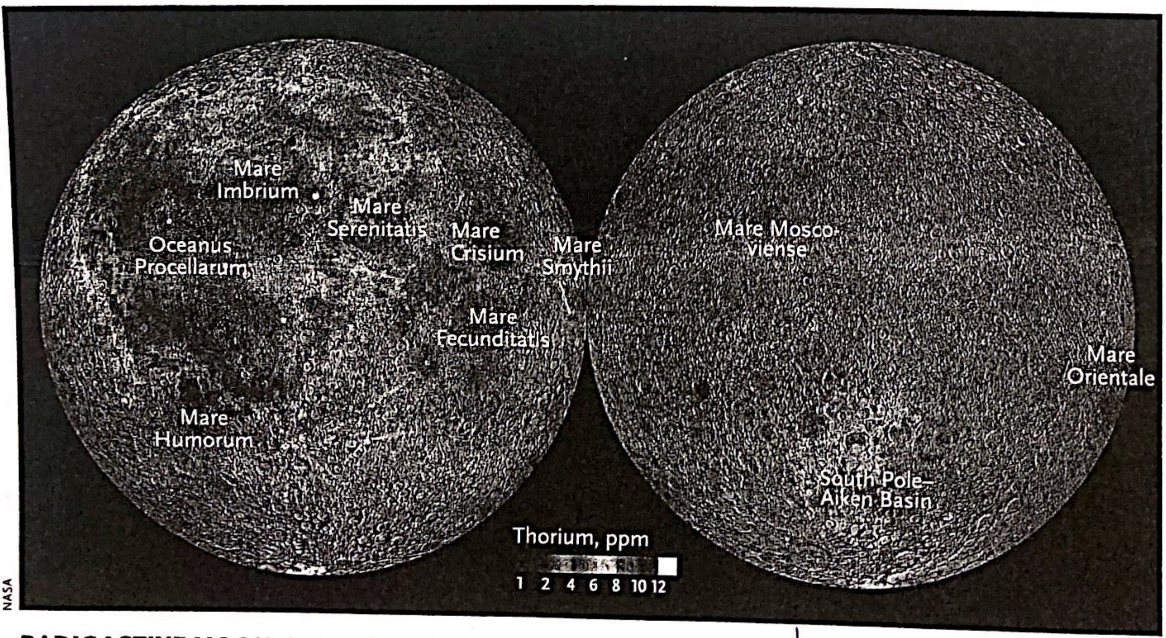
As shown by the 1998 Lunar Prospector mission, KREEP is not distributed evenly around the Moon. Instead, it's concentrated largely on the western nearside, within and around Oceanus Procellarum. A second, much lower concentration is found in the southern central farside, near the small maria on the floor of the South Pole–Aitken Basin, the largest (2,600 km) and oldest (perhaps 4.3 billion years) basin on the Moon. Because volcanism is driven by internal heat, scientists thought that high KREEP levels near the largest maria might mean that radioactivity had generated more heat in these places, resulting in the eruption of more lava. Higher KREEP abundances beneath the nearside than under the farside could explain why the Moon has two faces.

The difficulties in this case lie in two areas. First, the distribution of maria only partly correlates with high levels of radioactive elements. Although Procellarum is both very large and has lots of KREEP, other significant mare deposits occur in zones strongly *depleted* in such material. Such areas include both eastern nearside maria (such as Crisium, Smythii, and Fecunditatis) and some farside maria (Moscoviense and Orientale).

Second, the radioactive elements detected from orbit all occur within the topmost meter of the Moon's crust. Yet mare magmas are generated deep within the Moon, hundreds of kilometers lower. Any relationship between the surface and mantle compositions is likely to be both indirect and complex.

But even if the ultimate cause of the Moon's two-faced nature is a local enrichment of radioactive elements, this merely begs the question: why, then, are the heat-producing elements distributed unevenly on the Moon? There isn't a straightforward answer to this question, though some ideas have been proposed.

One recent paper suggested that since the surface of early Earth would have been molten after the impact that created the Moon, the radiant heat from this glowing sphere would have kept the Moon's nearside from cooling as quickly as the farside did. Such a temperature gradient between near- and farsides would supposedly lead to the creation of a chemical gradient, with a higher concentration of *refractory elements* (that is, those with high melting points, such as aluminum) on the farside. In this model, the thicker farside crust arises because



RADIOACTIVE MOON Spectra from the Lunar Prospector mission reveal levels of the radioactive element thorium on the lunar surface. Scientists think thorium, along with uranium and KREEP (potassium, rare earth elements, and phosphorous), helped melt the lunar interior, producing the magma that migrated to the surface to create the mare lava plains. But although the highest thorium concentrations appear in Oceanus Procellarum (orange and green area), maria locations don't necessarily match up with high radioactive levels.

RARE EARTH ELEMENTS

Rare earth elements are a group of metals that includes scandium, yttrium, and the 15 lanthanide elements (atomic numbers 57 through 71). They're used in many modern technologies, such as cell phones and hybrid-car batteries. In terms of abundance they're actually far more common in Earth's crust than gold, but they rarely exist in concentrations high enough to make mining economical.

that hemisphere initially had more refractory elements than the nearside.

But global maps of composition suggest that while regional differences do exist, they aren't primordial. Instead, these differences are the result of a complex history of impacts, mare flooding, and other geologic events that happened long after the Moon formed.

Another proposal is that the current near- and farsides were in a different configuration in the past and a large impact reoriented the Moon's spin axis, making the nearside mare dominated solely by accident. But even if such a scenario is true, it doesn't explain why there were two differing hemispheres to begin with.

A third idea proposes that a large "sub-moon" collided with the proto-Moon early in its history and plastered the farside with an additional rock layer as a "coating," creating the farside's highlands while at the same time "squeezing" that side's subsurface KREEP layer toward the nearside. Such an event does not align with our current understanding of how the impact process works. But even if it were feasible, there is no evidence that the Moon's farside contains any late-added, exotic rock types: farside compositions are similar (or identical) to those found globally around the Moon.

Thus, although these various scenarios can create double-faced Moons, all of the models proposed to date have a *deus ex machina* flavor, and science does not incorporate miracles into its explanations.

So we are left, at least partly, where we started. The Moon shows two faces, and the near- and farsides are different in many ways: maria vs. mostly highlands, thin crust vs. thick crust, and high levels of heat-producing elements vs. low levels of the same. These differences are probably related to differences in the lunar interior, some of which may date back to our satellite's formation. But we still only partly understand the history and processes involved in the evolution of the Moon. So why are the near- and farsides of the Moon so different? We don't know. ✧

***Paul D. Spudis** is a planetary scientist specializing in lunar history and processes. He is the author of* The Value of the Moon, *being published in April 2016 by Smithsonian Institution Press. More at* ***www.spudislunarresources.com**.*