# CATACLYSM'S END

*A popular theory about the early Solar System comes under fire.*

**BY ADAM MANN**

Early in Earth's history, roughly half a billion years after the planet formed, all hell broke loose in the inner Solar System. A barrage of asteroids — some the size of Hong Kong — pummelled the globe intensely enough to melt large parts of its surface. This incendiary spree around 4 billion years ago vaporized most of Earth's water and perhaps even sterilized its exterior, killing off any life that might have started to emerge. Only after this storm of impacts passed did the planet become safe enough for hardy organisms to take firm root and eventually give rise to all later life.

That horrific episode, known as the Late Heavy Bombardment (LHB), has been an integral part of Earth's origin story for decades, ever since geologists did a systematic study of samples brought back from the Moon by NASA Apollo missions. But now, the once-popular theory has come under attack, and mounting evidence is causing many researchers to abandon it. A growing community of planetary scientists thinks that things quietened down relatively quickly, with a steadily decreasing rain of asteroids that ended a few hundred million years after Earth and the Moon formed.

Settling the debate could have major ramifications for some of the biggest questions in geoscience: when did life emerge and what were conditions like on early Earth? But some researchers think that fresh samples will be needed to finally put this conundrum to rest. They are looking with hope at the United States' recent pledge to send astronauts back to the Moon — although no timeline has yet been set. In the meantime, the community is grappling with the fact that a key chapter of Solar System history might be vanishing before their eyes.

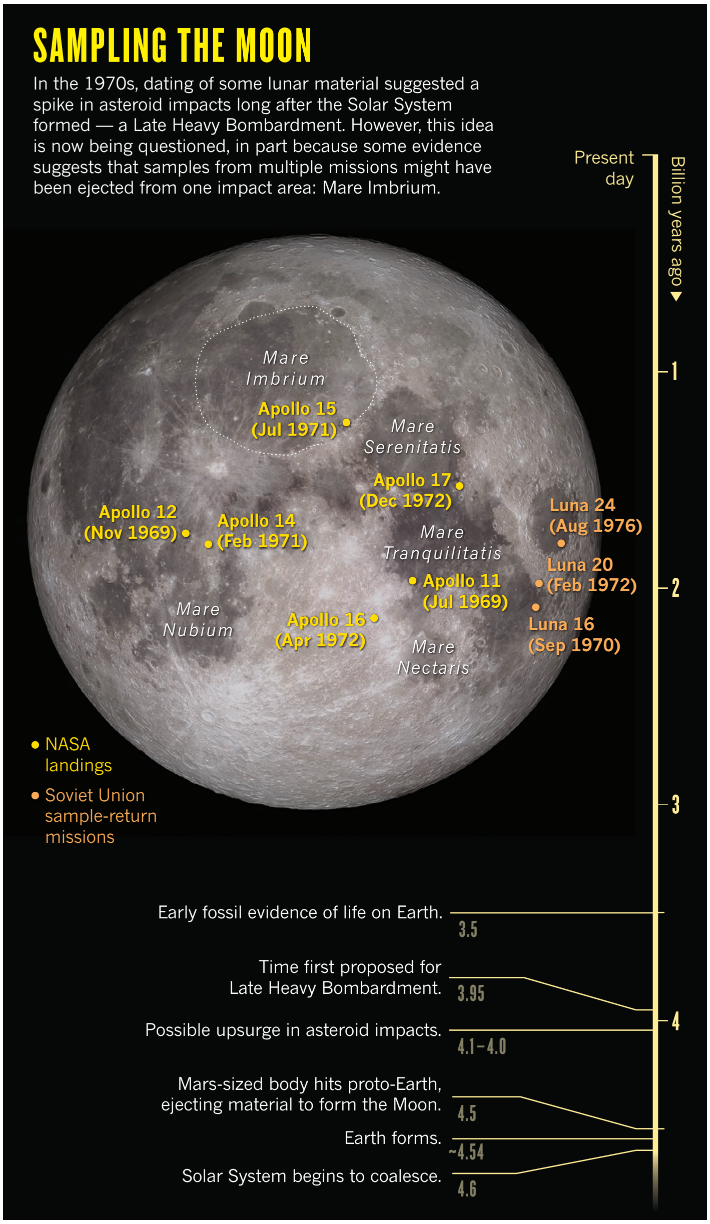
**An artist's impression of the early Earth, bombarded by Solar System debris.**

NASA/GODDARD IMAGE LAB

"The Late Heavy Bombardment was seen as one of the great triumphs of the Apollo era," says geochemist Mark Harrison of the University of California, Los Angeles. "There's no question that something has happened in the past few years that has profoundly upset the apple cart."

The Solar System formed some 4.6 billion years ago, after the centre of a massive cloud of gas and dust collapsed into a dense sphere that became our Sun. Pebbles in a dusty disk orbiting the star continuously collided and sometimes stuck together. After tens of millions of years, these agglomerations had built up into planetesimals — the beginnings of the planets. Other rocky fragments remained, crashing into their larger kin and leaving deep craters. Over time, the Solar System thinned out, leaving something like the configuration we see today.

Most of the evidence of this violent history has been erased on Earth by the churning of tectonic plates. But the scarred surface of the Moon, long inert, retains a lengthy record of impacts. Some of that record — roughly 382 kilograms of lunar rock and soil — was collected by Apollo astronauts and carried back to scientists eager to see what the samples might reveal about the Moon's history. In 1973, the year after the last Apollo landing, a group at Sheffield University, UK, reported a curious pattern in samples from four separate Apollo missions as well as a Soviet Luna mission. Radiometric dating of each one returned the same age: 3.95 billion years[1]. A team at the California Institute of Technology (Caltech) in Pasadena corroborated the findings the same year[2].




**SAMPLING THE MOON**

In the 1970s, dating of some lunar material suggested a spike in asteroid impacts long after the Solar System formed — a Late Heavy Bombardment. However, this idea is now being questioned, in part because some evidence suggests that samples from multiple missions might have been ejected from one impact area: Mare Imbrium.

MOON IMAGE: NASA

## CURIOUS CHRONOLOGY

The confluence of ages suggested that a flurry of objects struck the Moon in a narrow 50-million-year window, leaving behind countless impact craters — including as many as a dozen of the Texas-sized basins that scar the surface. Because it seemed to represent a final surge of pandemonium after the Solar System's chaotic genesis, the Caltech team named the event the terminal lunar cataclysm, although it later became more popularly known as the LHB.

The idea was immediately divisive, in large part because of ambiguity in the rock dating. This was done primarily by measuring the rocks' ratio of argon-40 atoms to radioactive potassium-40. $^{40}K$ decays into $^{40}Ar$ with a half-life of 1.25 billion years. At high temperatures, that $^{40}Ar$ can leak out of minerals. That makes the ratio of these two isotopes a kind of clock: the more time that has elapsed since a rock was hot, the more $^{40}Ar$ should be present. But making sense of the argon and potassium concentrations can be difficult because the same ratio could have been caused by a concentrated barrage that heated the rocks and released $^{40}Ar$ some 3.95 billion years ago, or by a long, dwindling asteroid torrent that released it in fits and starts before fizzling out at about the same time.

The first really new data arrived in 2000. Planetary scientist David Kring, cosmochemist Timothy Swindle and planetary scientist Barbara Cohen, all then at the University of Arizona in Tucson, collected lunar meteorites that had fallen to Earth after being blasted from the Moon's surface by asteroid strikes. They hoped such rocks would provide a more random sample of the Moon's crust than those from Apollo, which represent at most 4% of the lunar surface. But when the results came back, they showed a curious, and familiar, pattern.

"Frankly, I thought we'd measure a bunch of these and have ages running back to 4.3 and 4.4 [billion years] and prove once and for all that this whole idea was wrong," says Swindle. Instead, they found no evidence of impacts before the hypothesized time of the LHB[3]. "That kind of pushed me to a different side of the fence," he says.

But researchers still wondered how a bombardment could come so long after the Solar System formed. By the half-billion-year mark, most of the leftover debris should either have been cast out or have settled into stable zones such as the main asteroid belt, which sits between Mars and Jupiter, or the Kuiper belt beyond Neptune. Nobody could come up with a physical reason for the unexpected drama at such a late date. "Where did you have the bodies in the Solar System that could hang around for 600 million years and then come screaming in and hit the Moon?" asks Cohen, who is now at NASA's Goddard Space Flight Center in Greenbelt, Maryland.

A potential answer arrived in 2005, with the emergence of what came to be known as the Nice model, after the French city where it was conceived. Originally proposed to explain odd orbital behaviour by distant icy objects in the Kuiper belt, the conjecture asserted that the Solar System's outer planets had formed much closer to one another than they are now. Computer simulations showed[4] how the massive gravitational pull of Jupiter and Saturn could have created an instability that ultimately bumped Uranus and Neptune into more distant orbits, knocked comets out of remote reservoirs and kicked asteroids out of the main belt.

The Nice model offered huge support for the LHB. "I think this helped cement this idea," says physicist Nicolle Zellner of Albion College in Michigan. Geologist Marc Norman of the Australian National University in Canberra agrees. "That was the next real turning point," he says.

## CATACLYSMIC CONFUSION

Yet just when the idea of the LHB finally seemed unimpeachable, holes began to appear. Apollo data and 'crater counting', which estimates the order in which craters were laid down on the basis of how they overlap, had indicated that three of the largest crater basins on the Moon's near side — Imbrium, Nectaris and Serenitatis — might all be about 3.95 billion years old (see 'Sampling the Moon'). But high-resolution maps from NASA's Lunar Reconnaissance Orbiter, which started circling the Moon in 2009, spotted rays of debris extending from Imbrium[5]. This suggested that the impact that formed the crater might have knocked rocks into nearby Serenitatis, contaminating the Apollo samples picked up there. In 2010, a reanalysis of rocks thought to have been ejected from Nectaris indicated that they were also chemically and geologically similar to Imbrium material[6]. "We started realizing that maybe we were sampling Imbrium over and over," says Zellner.

The data from lunar meteorites didn't necessarily help. Although none of the samples seemed to be older than 4 billion years, some were billions of years younger than that[3], with no obvious spike around 3.95 billion years. And the Apollo samples held other surprises. Since 2012, detailed study[7] of microscopic regions in the rocks has turned up ages of as much as 4.2 billion years, much older than any seen before, suggesting that there had been significant impacts earlier than the proposed spike.

Prodded in part by these revelations, some researchers proposed[8] a longer-lasting LHB that began around 4.1 billion or 4.2 billion years ago. But that idea had one major strike against it: some of the most ancient crystals on Earth, from the Jack Hills range in Australia, suggest[9] that the planet was a fairly clement place then, with relatively low temperatures and ample water.

## HOT TOPIC

Others are still scrutinizing the original Apollo evidence. To determine the samples' ages, researchers heated the rocks to release argon, slowly ramping up the temperature. But as far back as 1991, Harrison had pointed out that the process won't work well for rocks containing multiple minerals. Different minerals will release their argon at different temperatures. A sample heated to 400 °C might provide an age of 2 billion years; to 500 °C, an age of 2.5 billion. Researchers have tried to extrapolate from this behaviour, but Harrison says the complex patterns often lead them to pick essentially arbitrary ages. "This is quackery," he says. "There's no physical basis for it."

Swindle says the argon heating situation is not necessarily as bad as Harrison makes it out to be; Apollo samples can be found whose ages don't change significantly with temperature, and their dates — whether they refer to one or multiple impacts — still cluster around 3.95 billion years. Cohen says that other chronometers, such as those using radioactive isotopes of rubidium and uranium, corroborate the argon ages (although Harrison counters that the dates can differ by as much as 600 million years).

Such back and forth underscores how difficult it can be to tease small clues out of extremely ancient rocks. "Sherlock Holmes was good at resolving mysteries that happened last year," says David Nesvorný, a planetary scientist at the Southwest Research Institute in Boulder, Colorado. "This all happened 4 billion years ago."

Meanwhile, the Nice model has proved less helpful to the idea of an LHB than it once seemed. More-advanced simulations of the early Solar System's gravitational interactions indicate that the planetary reshuffling probably happened shortly after formation, not with a delay of hundreds of millions of years[10]. Nesvorný likens delaying the reshuffling — and so keeping the Solar System hovering on the edge of instability — to trying to balance a pencil on its tip. "It's really hard to put the pencil there in such a way that it falls in an hour," he says.

> "PEOPLE SEE WHAT THEY WANT TO SEE AND DISREGARD THE REST."

One of the original architects of the Nice model, astronomer Alessandro Morbidelli of the Cote d'Azur Observatory in Nice, admits that the first versions took fine-tuning to get the reshuffling to occur so late. He no longer believes in the LHB, and sees many others in the field trading in the idea of a sudden asteroid deluge for that of a long, declining tail of bombardment. "My prediction is people will abandon the cataclysm," he says.

Even those who remain tied to the LHB have had to modify their ideas. Planetary scientist William Bottke of the Southwest Research Institute agrees that there is no longer much support for a single, short spike. He says the best reading of the evidence, including samples from ancient Earth and radiometric dates in meteorite rocks, is a more drawn-out surge of bombardment that began around 4.1 billion or 4 billion years ago, with a relative lull before that, consistent with the existence of surface water in that period.

Astronomer William Hartmann, a visiting scientist at the International Space Science Institute in Bern, thinks the current situation proves that the idea of a cataclysm was never particularly robust. Various research communities "kind of had the impression that the other community had really solved this", he says. "A paradigm structure was built up from supporting evidence, none of which was actually conclusive in itself."

If an LHB did not happen, that could make it easier to explain how life emerged. Evidence of microbial life has been found in rocks that are around 3.5 billion years old. But those fossils seem quite complex, suggesting that they had been evolving from earlier forms for at least a few hundred million years, during the originally hypothesized time of the LHB. Without the cataclysm, such an ancient genesis might make more sense. Then again, some evidence suggests that the microbes at the base of the tree of life were hyperthermophiles — that is, organisms that thrived in extreme heat. The intense conditions created by a rain of asteroids could have resulted in a number of pockets where life might have emerged.

So far, efforts to clinch the LHB debate with evidence from other likely victims — Mercury, Venus, Mars and objects from the asteroid belt — have proved inconclusive. Each camp accuses the other of cherry-picking favourable data and not looking at the total picture. "It's a Rorschach test," says Norman. "People see what they want to see and disregard the rest."

The only thing that researchers say will substantially move the needle is new samples from the Moon. Kring, now at the Lunar and Planetary Institute in Houston, Texas, has developed some concepts for sample-return missions, including one that would see astronauts collecting rocks from the South Pole–Aitken basin, the largest and oldest impact crater on the Moon. However, the next human mission to the Moon is still a long way off. The first new lunar rocks to be carried back to Earth may come from China's Chang'e-5, a robotic mission currently planned for 2019. It aims to collect samples from the volcanic Mons Rümker formation, an area younger than those explored by Apollo astronauts.

Although no single exploration effort is likely to end the dispute, researchers' improved understanding of the Moon and how to determine the ages of samples should provide greater confidence in the results.

However things eventually shake out, the new evidence will shift careers and rewrite textbooks. Yet, perhaps because of the long-lived nature of this debate, those trying to make sense of the LHB remain flexible, sceptical and surprisingly lighthearted.

"We are close friends and therefore we disagree all the time and then go drink a beer together," says Bottke. "One should carry models lightly and be prepared to drop them if something better comes along, because it happens all the time." ■

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