Pummeling the Planets

Scientists are debating whether the entire solar system suffered a barrage of impacts long after the planets formed.

EMILY LAKDAWALLA

Humans have evolved to appreciate Earth's blue sky, lush green forests, and oceans teeming with life. But our planet's beauty and serenity belies its violent history. The inexorable motions of Earth's tectonic plates, and the slow erosive power of wind and water, erase our planet's distant past. With no craters or rocks dating back more than 4 billion years, scientists must look elsewhere to uncover our solar system's early history.

Fortunately, just 239,000 miles away, the Moon's battered countenance preserves a record of a tumultuous past, when the solar system was not such a tranquil realm. Its overlapping impact basins are the marks left behind from a time when brutally large impacts were common.

The entire solar system must have suffered under the same rain of asteroids and comets. When scientists examine crater densities and measure the ages of rocks returned by the Apollo astronauts, they find that the bombardment may have been even fiercer than they imagined. The rocks showed evidence of alteration by impacts, leading researchers to conclude that nearly all the craters pockmarking the lunar highlands might have formed in a brief period, less than 100 million years long; and this cataclysm may have befallen the Moon and Earth not 4.5 billion, but instead 3.9 billion years ago — 600 million years *after* both worlds formed.

Nearly 2,000 impacts as large as, or larger than, the one that ended the reign of the dinosaurs would have resurfaced 80% of the Moon. Being a much more massive target, Earth would have suffered a cataclysm 10 times worse. The largest impacts would have gouged continent-sized basins, vaporized the oceans and even rocks, superheated the atmosphere, and seared the surface. Paleontologists have searched for evidence of life in Earth's oldest rocks, finding evidence of biologically influenced carbon isotopes 3.85 billion years ago. But with no rocks older than this, scientists can't tell whether nascent life on Earth was destroyed by a cataclysmic rain of debris.

This 4-billion-year-old conflagration has come to be known as the Late Heavy Bombardment (LHB). But was it really an unusual time in the Earth–Moon system, or was it just the tail end of a long history of pummeling? And if there really was a spike in the impact rate, what force of nature sent asteroids and comets cascading into the realm of the planets? The mystery of the LHB remains one of the most intractable and controversial puzzles in planetary science.

WHAM! Artist Don Davis portrays a large asteroid slamming into Earth some 4 billion years ago. If the Late Heavy Bombardment (LHB) occurred, and if lunar cratering rates are extrapolated to Earth, LHB impactors would have gouged about 20,000 craters at least 20 kilometers (12 miles) across, 40 basins with diameters of about 1,000 km, and several basins larger than 5,000 km. Earth would have suffered severe environmental damage about once a century. Complex life could not have survived the pounding.

Clues from the Moon

Everyone agrees that many more and much larger asteroids and comets were hitting the Moon 4 billion years ago than there are today. In 1966 William K. Hartmann (now at the Planetary Science Institute) studied photo maps of the Moon to determine that the battered highlands bore 32 times as many craters as the smoother maria.

Counting maria craters and comparing their density to that on the ancient rocks of northern Canada, Hartmann estimated the maria to be 3.5 billion years old. "I was lucky that it turned out about right," he remarks about this pre-Apollo research. But that ancient maria age implied an astonishing fact about the Moon's early history. "If there are 32 times as many craters, and they had to form in the first 700 or 800 million years, that means the early cratering rate was many hundreds of times higher than the rate we've seen since then."

Hartmann and other geologists assumed that this "early intense bombardment," as he called it, represented the end stages of the solar system's formation, the final days of planetesimals whacking one another to form the planets. By studying the Moon's highland rocks, we could learn about how the Earth and Moon were built. Geologists expected lunar samples to exhibit a wide variety of ages, indicating that rocks that congealed from large impacts formed at different times.

Geologists trained Apollo astronauts to look for "Genesis rocks" that would contain information about the period that has since been obliterated from Earth's geologic record. A dozen moonwalkers dutifully gathered and returned samples that had formed with the Moon's earliest crust, but had been altered in the tremendous heat of the impacts that created the giant basins. When Caltech geologists Fouad Tera, Dimitri Papanastassiou, and Gerald Wasserburg measured the rock ages, they were astonished to find that they all clustered within a relatively narrow window of time around 4 billion years ago, a period they called the "lunar cataclysm."

The combination of Apollo rock ages and careful study of the overlapping relationships between the ejecta deposits of nearside basins led Don Wilhelms (U.S. Geological Survey) to conclude in 1987 that 10 to 12 basin-forming

HISTORICAL ARCHIVE Without wind erosion, water erosion, and crustal plate motions, the Moon preserves a record of the solar system's early battering. The giant basins all date to about 3.9 billion years ago, suggesting a frenzy of impactors 600 million years after the planets formed. But it's also possible that the impact rate remained high long after the planets formed, and the basins preserve the last gasp of the severe rain of large planetesimals that accompanied planet formation.

S&T: SEAN WALKER

impacts, from Nectaris as the oldest to Imbrium as the youngest, occurred within a span of only 70 million years, from about 3.92 to 3.85 billion years ago, supporting the lunar cataclysm.

Not all scientists embraced the lunar cataclysm, to put it mildly. A fundamental problem was that nobody could explain how or why a population of bodies large enough to create the Moon's basins (tens to hundreds of kilometers in diameter) would wait around for 600 million years and then suddenly get flung into orbits that intersected the Earth–Moon system. Moreover, the lunar highlands are saturated with impact craters, meaning each new crater destroys a previous one. Pre-cataclysm lunar basins could have been erased by later impacts. The Moon has an ancient surface, but it might not be old enough to tell us exactly what was going on more than 3.9 billion years ago.

Apollo Samples Aren't Enough

For years, everyone knew that a potential bias lurked in the Apollo age data. To facilitate radio communications, the Apollo landers had to touch down on the Moon's near side, and not far from the equator. As a result, every mission may have sampled the impact that excavated the enormous Imbrium basin. Even Tera and his collaborators recognized this possibility in their original paper.

Arguments that the Apollo samples might be biased

HUMAN SAMPLE RETURN Apollo 17 astronaut and geologist Harrison Schmitt was the only moonwalker who was a trained scientist. In this image, taken by Eugene Cernan, Schmitt is collecting a sample to bring back to Earth. Apollo rocks all date to about the same time, but they came from a chemically anomalous region of the Moon.

were bolstered by results from a gamma-ray spectrometer on NASA's Lunar Prospector, which orbited the Moon in 1998–99. That instrument measured the abundance of chemical elements with radioactive isotopes. When the Lunar Prospector map was published, lunar scientists were surprised — and chagrined — to discover that the Apollo landing sites clustered in a geochemically anomalous area whose surface appears unusually rich in potassium (K), rare-earth elements (REE), phosphorous (P), and other elements, collectively referred to as KREEP. (Seriously.) The KREEP signal blazed from the area surrounding the Imbrium impact.

Scientists have found more than 150 lunar meteorites from places outside the KREEP terrain, coming from perhaps 60 different spots on the Moon. Unlike the Apollo samples, lunar meteorites should represent a random sampling of rocks from both the Moon's near side and far side. Indeed, the lunar meteorites turned out to be far less KREEPy (a term that's actually in general use!) than the Apollo samples. "We don't know exactly where each meteorite comes from," says planetary scientist Barbara Cohen (NASA/Marshall Space Flight Center), "but they're not from the same sites as Apollo."

In the 1990s, laboratory techniques finally permitted the age dating of the tiny blebs of impact melt preserved in lunar meteorites. "When I was researching my doctoral dissertation," says Cohen, "I naïvely thought for sure I was going to nail this; I was going to find the 4.0-, 4.2-, even 4.4-billion-year-old impact-melt rocks, and I was going to solve the puzzle, and it was going to be awesome."

In fact, Cohen found nothing older than 3.94 billion years of age in any of her samples. She and her University of Arizona colleagues, Tim Swindle and David Kring, published a paper in 2000 announcing that their results supported the lunar-cataclysm hypothesis. But other scientists disagreed.

Hartmann was one of their critics. "When they gave that paper at meetings, I would say, 'Your data don't have a spike in impact ages at 3.9 billion years ago, so I don't understand how you can say it supports a cataclysmic shower of impacts at that time. Lack of samples before 4.0 doesn't prove that a burst of impacts happened at 3.9!'"

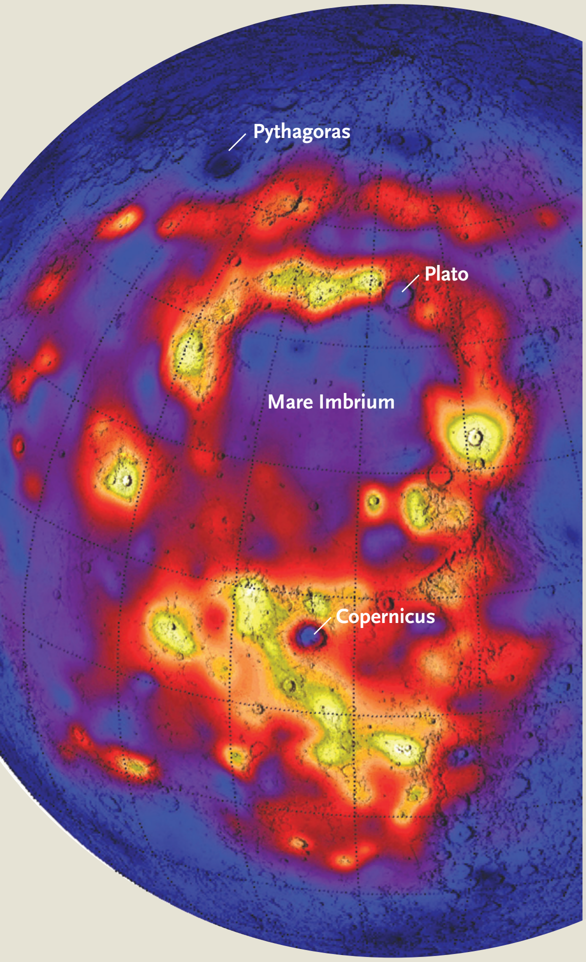
Cohen agrees that the puzzle is not yet solved. "The lunar meteorites show us is that it's not easy to find pre-3.94-billion-year-old impact-melt rock. But what that fact means is still a topic of scientific debate." There may have been a heavy bombardment 3.9 billion years ago, but it might have been just as heavy before then.

Some scientists think that a robotically retrieved lunar sample from the oldest impact site on the Moon, the South Pole-Aitken Basin, might resolve the question of whether there was a lunar cataclysm. Cohen belongs to a team that has proposed MoonRise, a mission in NASA's New Frontiers program, to do just that.

Hartmann remains unconvinced, "I'm really worried whether the returned rocks would actually give the date of the impact of the South Pole-Aitken Basin," he says. After all, explains Hartmann, maybe the samples would simply repeat the Apollo bias problem. The MoonRise team's research suggests such concerns are unfounded. "If we

RANDY KOROTEV (WASHINGTON UNIVERSITY IN ST. LOUIS)

LUNAR METEORITES This rock, known as Yamato 86032, is one of the 150 known lunar meteorites, and it's one of the largest lunar meteorites found in Antarctica. Unlike the Apollo rocks, lunar meteorites come from all over the Moon. Yet most of them show evidence for melting events about 3.94 billion years ago, probably from basin-forming impacts. This particular meteorite is lacking in KREEP elements.



KREEPY SIGNAL The gamma-ray spectrometer aboard NASA's Lunar Prospector orbiter returned data that scientists converted into this map of the near side. The bright area shows an enhanced concentration of thorium. This element is a trace element in the lunar regolith that indicates the presence of potassium (chemical symbol K), rare-Earth elements (REE), and phosphorous (P). The elements are collectively known as KREEP. The Apollo missions all landed in or near the KREEP zone, which means the astronauts returned chemically anomalous rocks. The lunar far side generally lacks the enhanced thorium signatures seen on the near side.

DAVID J. LAWRENCE (JHU / APL), ET AL.

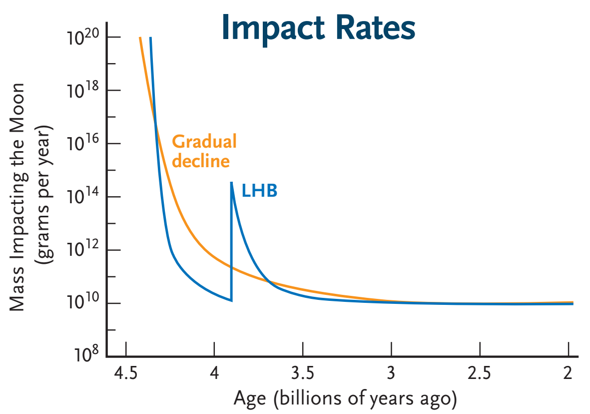
pick an appropriate landing site, we'll get what we need," says Cohen.

It's Neptune's Fault

Meanwhile, other researchers have attempted to explain what could have caused a pulse in impacts long after the planets accreted. For example, perhaps there were enough leftover materials from the accretion process to cause the terminal bombardment. Unfortunately, models of solar-system formation suggest that accretion was essentially complete within 100 million years, much sooner than the time of the cataclysm. Others have suggested that a massive collision in the asteroid belt broke up a Ceres-sized object that resulted in a pulse of impactors being redirected toward the inner solar system. But an object as large as Ceres (about 480 km across) is difficult to disrupt.

Then came the Nice Model (*S&T:* September 2007, page 22). Named for the beautiful French seaside city in which it was developed in 2004 by Hal Levison (Southwest Research Institute) and three coworkers, the Nice Model was motivated by an attempt to explain the orbital eccentricities of Jupiter and Saturn, and then how planets as massive as Uranus and Neptune could have formed so far from the Sun.

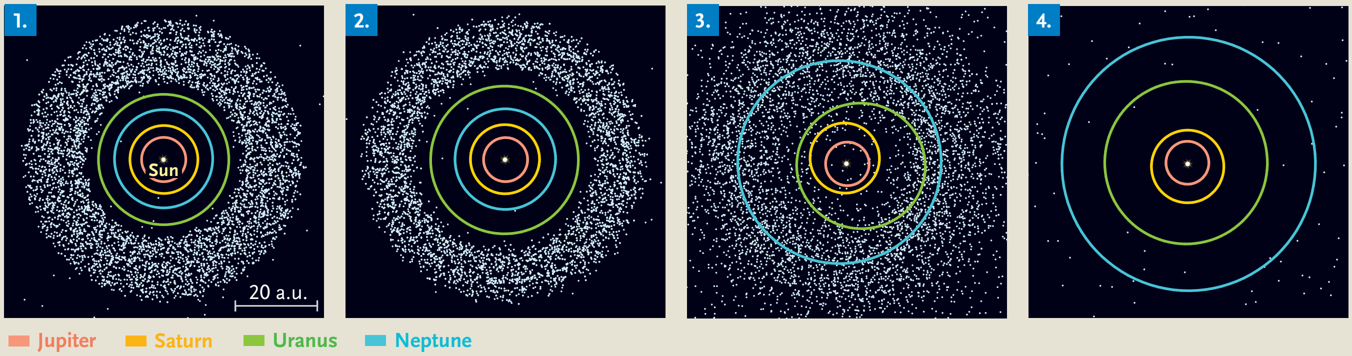
The Nice Model begins with the giant planets in a more compact configuration, surrounded by a cloud of planetesimals (the precursor of today's Kuiper Belt) that had about an Earth mass. Jupiter and Saturn migrated through a 2:1 or other orbital resonance, producing a gravitational chain reaction that sent Neptune plowing into the planetesimal disk (a new version of the Nice Model, to be published in the future, will invoke a different trigger). "That disk goes kaplooey," says Levison. "It scatters bodies all over the solar system, part of it raining down and hit-



IMPACT RATES This graph compares a proposed lunar impact rate with the LHB (blue) and without the LHB (orange). Note the dramatic difference between the two scenarios.

SOURCE: CHRISTIAN KOEBERL (UNIVERSITY OF VIENNA)

The Nice Model



SOURCE: HAL LEVISON (SW RESEARCH INST.), ET AL. (4)

THE NICE MODEL Computer simulations depict a possible chaotic phase in our solar system about 600 million years after it formed. *1.* Jupiter and Saturn start off at 5.5 and 8.2 astronomical units (a.u.). Neptune (at 11.5 a.u.) starts off closer than Uranus (14.2 a.u.). A disk of icy planetesimals, the precursor of today's Kuiper Belt, extends from 15 to 35 a.u. *2.* As the giant planets scatter comets into deep space, Jupiter migrates inward to about 5.2 a.u. The other three planets migrate outward. *3.* Jupiter and Saturn briefly pass through a 2:1 orbital resonance that gravitationally perturbs the orbits of Uranus and Neptune. The two outermost planets exchange position, and their highly elongated orbits carry them into the Kuiper Belt, where they begin scattering enormous numbers of planetesimals, some of which bombard the inner planets. *4.* The outer planets settle into their final orbits, leaving behind a severely depleted Kuiper Belt. Jupiter's inward migration also destabilizes the asteroid belt, sending swarms of bodies into the inner solar system.

ting the Moon, and everything else."

The Moon, being a relatively small target with low gravity, would have been one of the *least* damaged bodies. The wayward comets destabilized the asteroid belt as well; so bodies in the inner solar system, from Mercury to Mars, received a double whammy. The Earth–Moon system (along with Mercury, Venus, and Mars) would have been hammered by roughly equal numbers of comets and asteroids. Because of its proximity to the asteroid belt, Mars would have suffered as badly as more massive Earth; the number of cometary impacts alone could have delivered a volume of water equivalent to 5% that of Earth's oceans.

The hailstorm of comets would have been even more intense in the outer solar system. Ganymede, twice as massive as our Moon and close to gargantuan Jupiter, would have suffered 80 times as many comet crashes as our Moon. So many impacts at such a high rate may have melted Ganymede's upper layers of ice and kick-started its internal geology. Similarly sized Callisto was somewhat spared because being farther from Jupiter, it would have felt "only" 40 times the lunar impact rate, and experienced lower-velocity crashes.

This rain of impactors is really just a byproduct of the Nice Model, which also explains the sizes, shapes, and inclinations of the orbits of the giant planets and all the smaller pieces of the outer solar system. "We explain Jupiter's Trojan asteroids and we make the irregular satellites and we get the right orbital-element distribution in the Kuiper Belt," says Levison. "We get the outer edge of the Kuiper Belt. We get the extended scattered disk. We get the orbits of the giant planets right, too. Before the Nice Model we didn't really have good explanations for any of these things. The Nice Model gives us all of them. And the more we push it, the better it seems to work."

Suddenly there was a mechanism to deliver a late pulse of comets and asteroids to bombard the Moon and every object in the solar system 3.9 billion years ago. According to Cohen, this came as a huge relief to scientists who were trying to justify the LHB. "Even if this specific model is wrong, the fact that they're showing that you could have bodies winging around the solar system hundreds of millions of years after it formed makes it easier for the community to think about the lunar cataclysm as something that could be real."

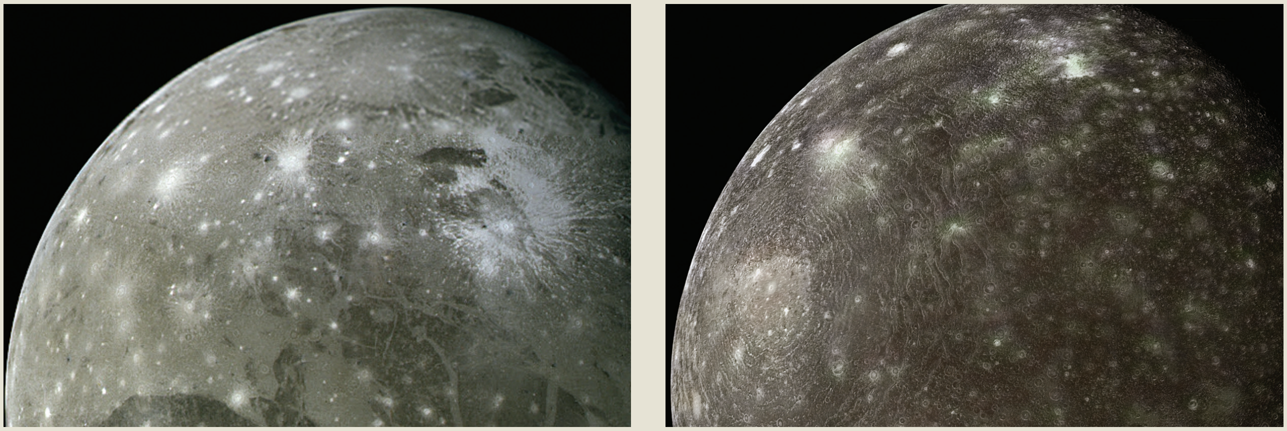
WHAT ABOUT MARS?

Like the Moon's heavily cratered terrain, Mars's southern highlands preserve a record of a heavy bombardment in the ancient past. But it might be too young to reveal what was happening more than 3.9 billion years ago.

Topography data from the laser altimeter aboard NASA's Mars Global Surveyor orbiter, and model crustal thickness data, revealed about 30 buried and visible impact basins larger than 1,000 kilometers across on the Red Planet. Recent studies by Herbert Frey (NASA/Goddard Space Flight Center) find that these largest basins cluster within a narrow window in time, with no evidence for prior large impacts. The Late Heavy Bombardment predicted by the Nice Model would produce exactly this kind of pattern.

Frey and his colleague Rob Lillis (University of California, Berkeley) have suggested that the LHB played a role in the demise of Mars's global magnetic field, which left the planet's atmosphere unprotected from the ravages of the solar wind. If true, the LHB was a major factor in eroding the Martian atmosphere, turning what had been a warm-and-wet planet into a frigid desert wasteland. — *Robert Naeye*

NASA / JPL / DANIEL MACHÁČEK (2)



BATTERED WORLDS The LHB would have profoundly affected the entire solar system, including the outer planets and their moons. Jupiter's gravity would have drawn wayward objects toward it, exposing its moons to a horrendous pounding. *Left:* Ganymede lacks impact craters because geological activity erased many of its ancient scars. *Right:* Callisto has remained inactive for billions of years, so its surface bears numerous impact craters. The outer rings of the Valhalla impact basin (bright region at lower left) extend 1,500 km from the center. Amateur astronomer Daniel Macháček assembled the mosaics from Galileo (Ganymede) and Voyager (Callisto) images.

Even Hartmann, a lunar cataclysm skeptic, acknowledges the beauty of the Nice Model. But he points out that "the model itself does not tell you when this surge of cratering occurred." When the impact spike occurs in the Nice Model depends largely on the choice of the disk's initial mass outside the orbits of the giant planets.

Evidence Under Our Noses

Meanwhile, another line of research is opening a new window into the earliest days of the solar system. Geologists have discovered that a few extremely hardy mineral crystals, notably zircons (zirconium orthosilicate, or $ZrSiO_4$), are practically indestructible. Once they crystallize in magma, they're almost impossible to melt (melting only at temperatures higher than 1000°C). They don't dissolve in hot or acidic fluids, and they only reluctantly give up any elements trapped within them even when heated to near-melting temperatures. As terrestrial rocks have been eroded, reburied, and even partially melted in the roots of ancient mountains, ancient zircons have survived.

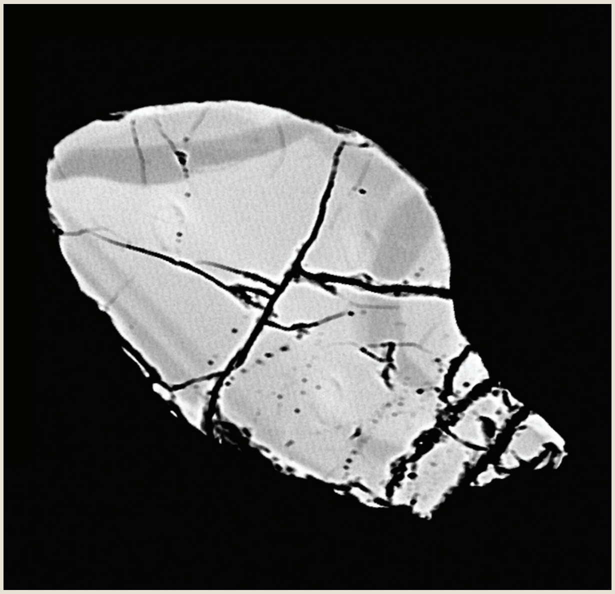
Geochemist Stephen Mojzsis (University of Colorado) and his collaborators have dated 200,000 individual zircon crystals. The oldest zircon comes in at a whopping 4.38 billion years in age, predating Earth's oldest known rocks by more than 300 million years.

The researchers have recently developed a technique by which they use an ion microprobe to burn slowly into single microscopic zircon crystals, analyzing minuscule quantities of uranium, thorium, and lead isotopes to arrive at an age-to-depth profile through the zircon grain. All 10 zircon crystals that Mojzsis has so far depth-profiled — which come from rocks of different ages — contain a region only a few micrometers wide that records a sharp pulse of heating at 3.96 billion years ago. The crystals, and presumably the rocks they resided in, had been heated to temperatures around 1200°C for a period of only months. "This was remarkable," says Mojzsis. "There really isn't any geological condition on Earth that can do that, but impact melt sheets can."

None of the zircons show evidence for any similar pulse of heat earlier than 3.96 billion years ago, going back to 4.3 billion years. "It's not proof of the Late Heavy Bombardment on Earth, but it's compelling," says Mojzsis.

One might conclude that an intense bombardment of the early Earth would have wiped out any nascent life

STEPHEN MOJZSIS (UNIVERSITY OF COLORADO)



MINI TIME CAPSULE This electron microscope image shows a 200-micrometer-wide zircon from Western Australia. Its core crystallized 4.18 billion years ago. A flash heating event 3.96 billion years ago, possibly from an impact, produced the curved bands near the edge. The heating age matches that of the LHB.

forms, and that all creatures living today descend from microbes that originated after the LHB. But recent mathematical modeling by Mojzsis and his colleague Oleg Abramov have produced surprising results. Even though any individual LHB impact would have sterilized the surrounding crust, there would have been plenty of refugia for unicellular life, especially for microscopic critters that loved the high-temperature fluids that percolate around volcanically active zones. So life could have originated on Earth more than 4 billion years ago and survived the LHB, but evidence for that epic event may be lost forever.

Solving the Puzzle

Hartmann, Cohen, and Mojzsis all agree that garden-variety meteorites from the asteroid belt are an underutilized resource in addressing the LHB mystery. Early data suggest that age dates among meteorites do not show a sharp spike at 3.9 billion years, but the number of analyzed samples remains small.

What about Martian meteorites? Mojzsis says we have one date from a single Martian rock, the famously controversial Allan Hills 84001, which shows that the 4.5 billion-year-old rock suffered a heating event at — guess what? — 3.9 billion years ago.

After five decades of interplanetary missions, we still don't know whether the solar system's violent infancy tapered off gradually into a sedate adulthood, or if there were tempestuous teen years. The maddening puzzle of the Late Heavy Bombardment will motivate researchers for decades to come. ✦

To watch a video of the Nice Model, visit SkyandTelescope.com/LHB.

Planetary Society web editor and S&T *contributing editor* ***Emily Lakdawalla*** *blogs daily at planetary.org/blog. She is the 2011 recipient of the prestigious Jonathan Eberhart Planetary Sciences Journalism Award from the American Astronomical Society's Division for Planetary Sciences.*

Did the Late Heavy Bombardent Flame Out or Fizzle Out?

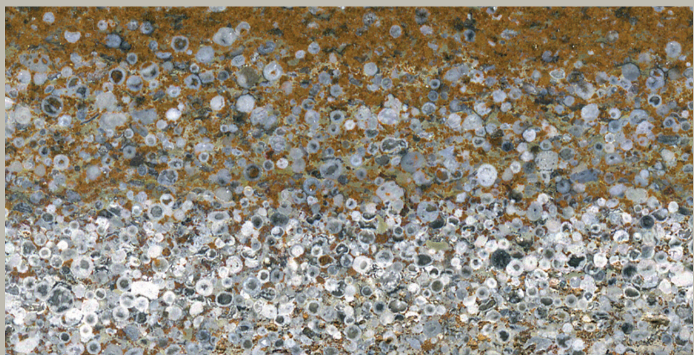
FOR YEARS, planetary scientists assumed that if the LHB was for real, it ended almost as abruptly as it began. But recent geological discoveries suggest it might have tapered off gradually, with Earth continuing to suffer enormous impacts long after the LHB's initial pulse.

The evidence comes from rocks in Western Australia and South Africa, the only known places that preserve sediments from 3.8 to 2.5 billion years ago. Geologists Donald Lowe (Stanford University), Gary Byerly (Louisiana State University), Bruce Simonson (Oberlin College), and others have found numerous well-preserved layers of spherules containing extraterrestrial material embedded in these ancient strata. The thickest layers span several centimeters, much thicker than the 3-millimeter layer found between Cretaceous and Tertiary sediments. These beefier layers suggest that the largest impacting objects were considerably bigger than the 6-mile-wide impactor that hit 65 million years ago and wiped out all dinosaurs except birds. Based on the spacing of the layers, ancient Earth suffered a giant impact every 40 to 50 million years, compared to the modern rate of one every several hundred million years.

A recent dynamical study by Bill Bottke (Southwest Research Institute) and his colleagues suggests that the impactors responsible for the LHB's extended tail originated in the "E-belt," an inner extension of the main asteroid belt that once stretched nearly to Mars. If the Nice Model is correct, E-belt bodies were scattered about 4 billion years ago when the giant planets began their late migration. Some of these asteroids ended up smashing into the Earth and Moon. The few surviving E-belt members make up the Hungaria asteroids, whose members have highly inclined orbits between 1.8 and 2.0 astronomical units.

Bottke points out that the largest LHB impacts ended by 2.5 billion years ago, which coincides with the rapid buildup of oxygen in Earth's atmosphere. Further research may reveal whether this was just a coincidence, or whether our planet had to wait for the LHB to fizzle out before it could start developing the conditions necessary for the evolution of complex, multicellular life.

S&T *editor in chief* ***Robert Naeye*** *is glad he wasn't around to experience the fury of the LHB.*



BRUCE SIMONSON (OBERLIN COLLEGE)

IMPACT SPHERULES This close-up photo of a 2.54-billion-year-old rock from Western Australia shows a 1-cm-thick layer of spherules at the bottom, with the largest spherules being about 1 mm across. The spherules formed during the intense heat of an impact, and consist of target rock and a few percent extraterrestrial material. The spherules flew into space as molten balls and rained back to Earth. The surrounding layers are solidified seafloor mud. Geologists have found at least 10 similar layers in ancient strata from Western Australia and South Africa, suggesting that LHB impactors continued to hit our planet until 2.5 billion years ago.