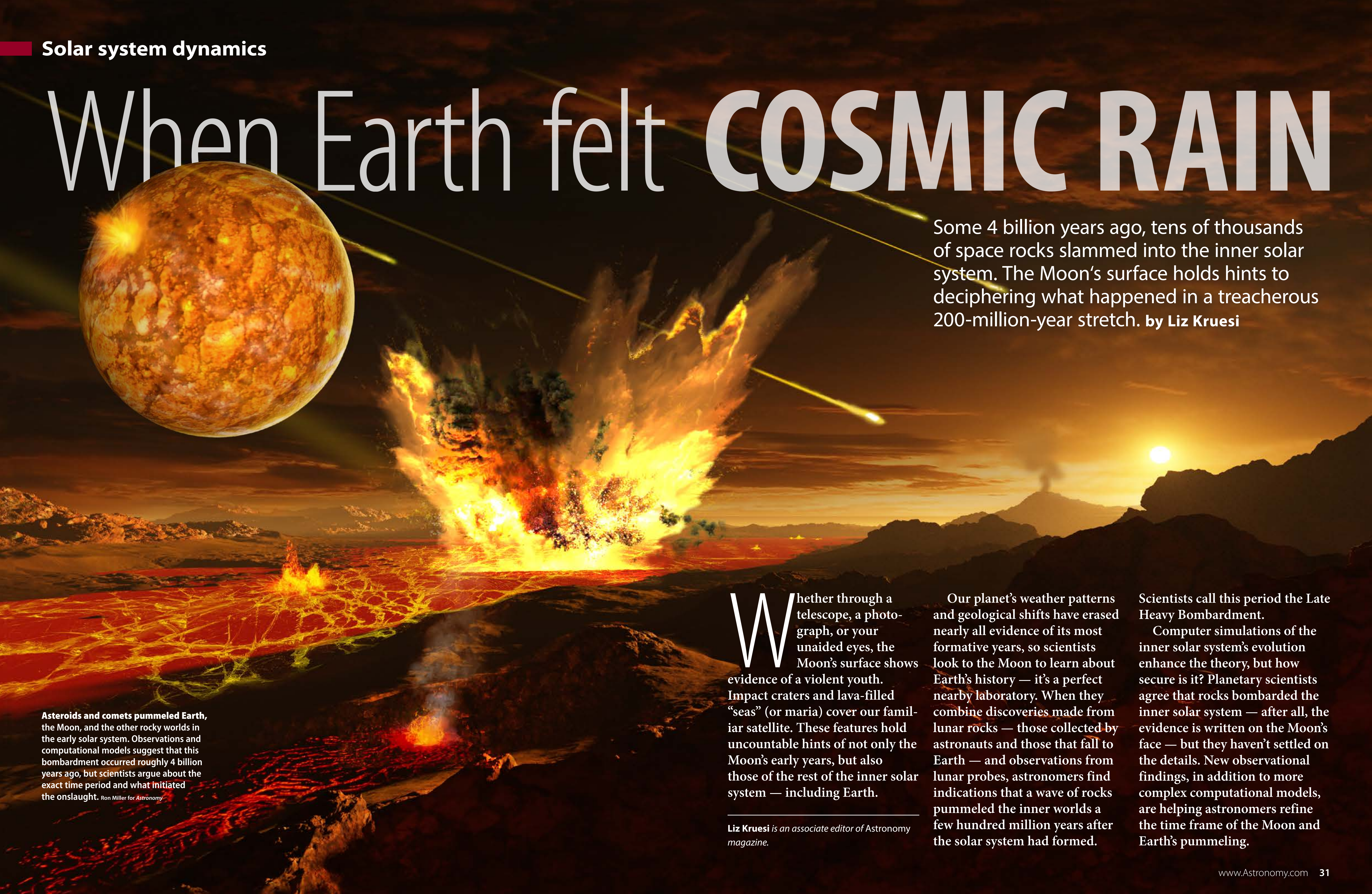
When Earth felt COSMIC RAIN

Some 4 billion years ago, tens of thousands of space rocks slammed into the inner solar system. The Moon's surface holds hints to deciphering what happened in a treacherous 200-million-year stretch. **by Liz Kruesi**



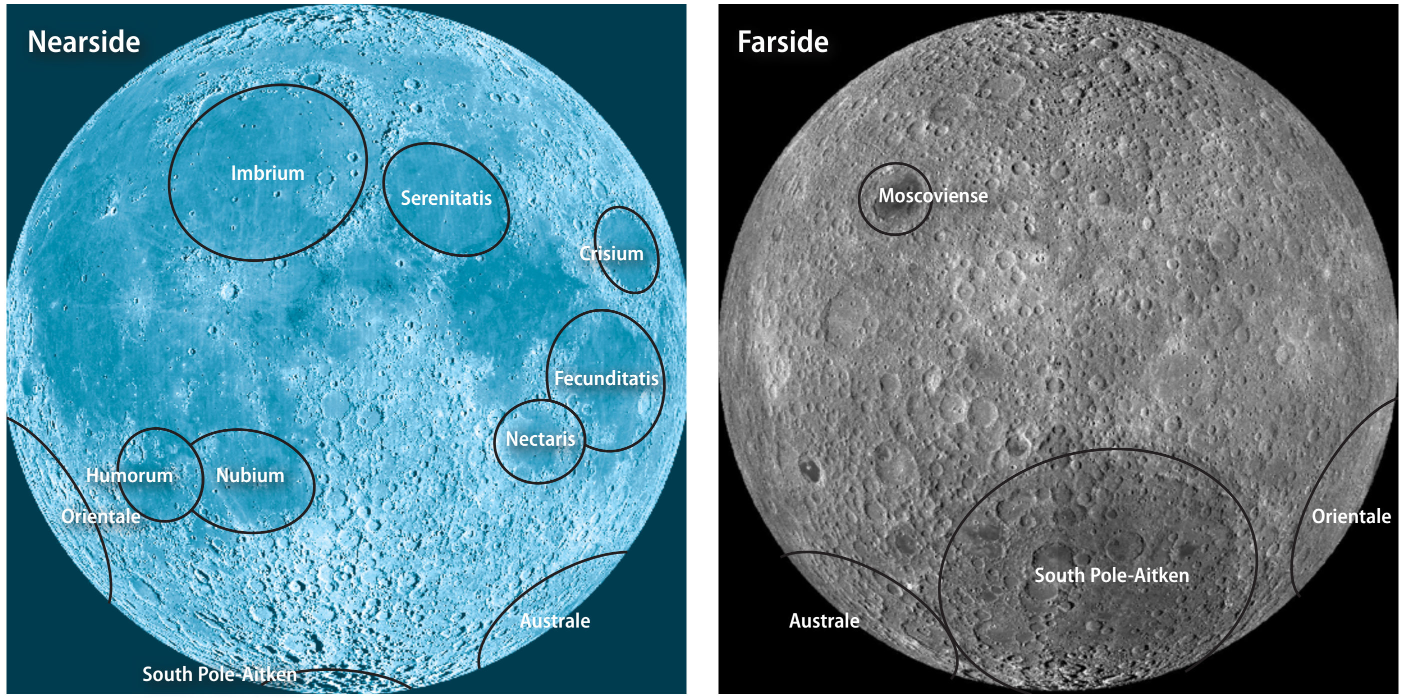
Asteroids and comets pummeled Earth, the Moon, and the other rocky worlds in the early solar system. Observations and computational models suggest that this bombardment occurred roughly 4 billion years ago, but scientists argue about the exact time period and what initiated the onslaught. Ron Miller for *Astronomy*

Whether through a telescope, a photograph, or your unaided eyes, the Moon's surface shows evidence of a violent youth. Impact craters and lava-filled "seas" (or maria) cover our familiar satellite. These features hold uncountable hints of not only the Moon's early years, but also those of the rest of the inner solar system — including Earth.

Our planet's weather patterns and geological shifts have erased nearly all evidence of its most formative years, so scientists look to the Moon to learn about Earth's history — it's a perfect nearby laboratory. When they combine discoveries made from lunar rocks — those collected by astronauts and those that fall to Earth — and observations from lunar probes, astronomers find indications that a wave of rocks pummeled the inner worlds a few hundred million years after the solar system had formed. Scientists call this period the Late Heavy Bombardment.

Computer simulations of the inner solar system's evolution enhance the theory, but how secure is it? Planetary scientists agree that rocks bombarded the inner solar system — after all, the evidence is written on the Moon's face — but they haven't settled on the details. New observational findings, in addition to more complex computational models, are helping astronomers refine the time frame of the Moon and Earth's pummeling.

Liz Kruesi *is an associate editor of* Astronomy *magazine.*



The largest lunar impacts formed basins on the surface, and they often have double-ring structures. Astronomers haven't collected enough samples from the Moon to accurately date the basins, but their ages are around 4 billion years old. NASA/GSFC/Arizona State University

Growing up in turmoil

The solar system began with a "protoplanetary" disk of gas and dust surrounding the Sun. This was a dangerous time in our neighborhood's evolution, with a lot of loose material — some large, and a plethora of small rocky bodies — traveling on random orbits. The planets started forming out of this material around 4.6 billion years ago. About 100 million years into this process, a Mars-sized rock still whizzing around the solar system likely slammed into the early Earth. Material from both the impactor and our nascent world's surface was thrown into space, and debris coalesced to create the Moon.

According to early planetary theories, after a few tens to hundreds of millions of years, the number of small rocky bodies, called planetesimals, declined; they were either swept up by planets or smashed into dust. Scientists expected the solar system's impact history to have slowed dramatically. Thus, if researchers could obtain samples of the largest impact craters on the lunar surface, these ancient rocks would date to around the time the Moon formed and shortly after.

But when six Apollo missions brought back 842 pounds (382 kilograms) of lunar rocks, core samples, pebbles, sand, and dust from the Moon's surface, researchers got a surprise. After analyzing these samples using radiometric dating techniques, which measure the abundance of certain elements in the rocks and compare those amounts to a fresh sample, they found that most of the lunar material dated to about 4 billion to 3.85 billion years ago — hundreds of millions of years *after* the Moon formed. "A big surprise was that it was hard to find rocks older than 4 billion years," says William Hartmann of the Planetary Science Institute in Tucson, Arizona.

Fast fact

It wasn't only the Apollo missions that brought back Moon rocks. Three of the Soviet Union's Luna spacecraft collected some 11 ounces (300 grams) of lunar material from the highlands.

A team of scientists at the California Institute of Technology in Pasadena proposed in 1974 that the Apollo samples indicated a spike in the number of small bodies slamming into Earth's satellite. As the rocks pummeled the lunar surface in a brief 100 million years or so, they wiped out nearly all of the older material, leaving behind a surface "remade" around 3.85 billion years ago. The paper's co-authors — Fouad Tera, Dimitri Papanastassiou, and Gerald Wasserburg — called this period the lunar cataclysm, but it later also took on the name Late Heavy Bombardment.

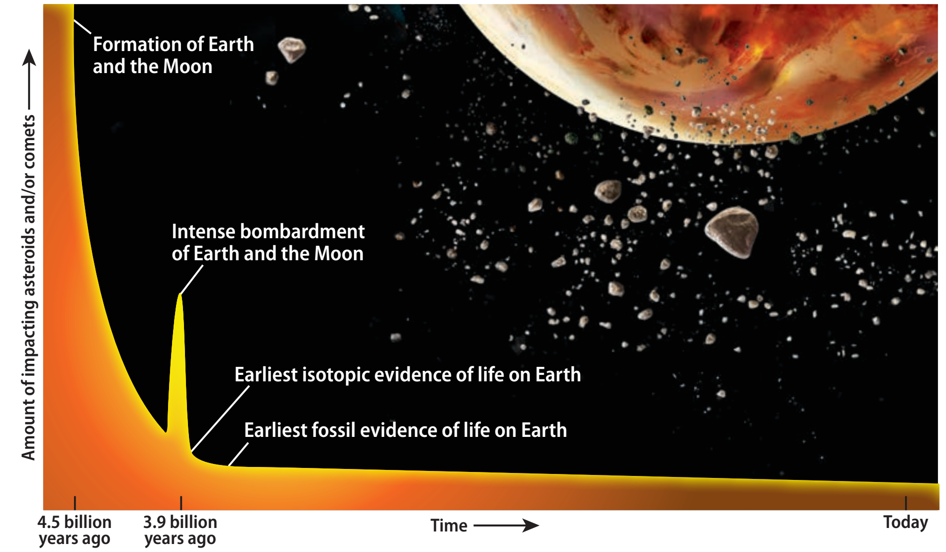
Evidence in our backyard

Almost as soon as Tera and colleagues proposed their theory, other planetary scientists disagreed with it. The Apollo rocks came from areas near one another on the Moon's nearside; could all the samples have been created in the same impact? The Imbrium Basin is the largest on the nearside and also one of the Moon's youngest; some scientists argued that ejecta from its formation could have scattered across the lunar surface, and that astronauts might have collected this material instead of a random sample. Planetary scientists needed more evidence.

Impacts on the Moon also launch debris into space, and some of it will land on Earth after millions of years. Since the 1980s, scientists have found these lunar rocks on our planet and analyzed their compositions to determine their ages. Because impacts can happen on any area of the Moon, this thrown-off debris is much more random and thus represents a larger region than the rocks collected by the Apollo missions. But researchers found that the ages of lunar meteorites are also younger than 4 billion years old.

Questions still remained, though: Where did the bombarding material come from? Was there an additional reservoir of small rocky bodies that had evaded the solar system's planet evolution? And what disturbed the orbits of these asteroids and/or comets that caused them to slam into the inner solar system?

When cosmic rain fell



The Late Heavy Bombardment earned its name because evidence indicates that an enormous number of small bodies slammed into the terrestrial planets and the Moon hundreds of million years after the solar system formed. *Astronomy*: Roen Kelly, after David Kring of the Lunar and Planetary Institute

Consulting silicon

Computer modeling offered a way to put the pieces together. A simulation published in 2005 from a team of researchers based at the Observatoire de la Côte d'Azur in Nice, France, provides insight into the evolution of the inner solar system. In particular, it suggests that the outer planets (Jupiter, Saturn, Uranus, and Neptune) likely formed nearer to each other and closer to the Sun than they are now. The model implies that after the protoplanetary disk evaporated, the giant planets originally existed between 5 and 17 astronomical units (AU, where 1 AU is the average Earth-Sun distance) from our star. Just outside the farthest planet sat a disk of small rocky objects that extended to about 35 AU.

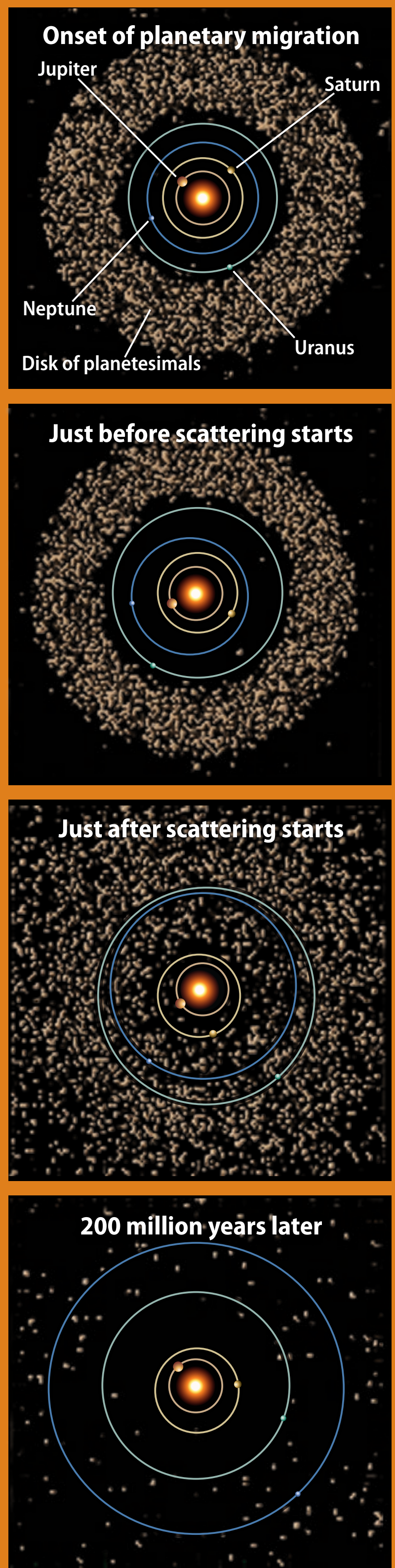
According to the Nice model, as it's called (and pronounced "niece"), the orbits slowly "wiggled" over time. After a few hundred million years, Jupiter and Saturn passed through orbits that coincided with a 2:1 resonance (meaning Jupiter made two revolutions around the Sun for every one that Saturn made). The combined gravitational effect forced Jupiter, Saturn, Uranus, and Neptune to disperse from one another. As the planets interacted, they tweaked the orbits of any small objects in their paths. Uranus and Neptune both moved into the planetesimal disk, scattering small bodies everywhere. (See "The Nice model" on page 34.)

This is the point in the model that offers an explanation of the lunar cataclysm scenario: Those scattered rocky bodies would have made it into the inner solar system. This model also matches other observations in the present-day solar system, so it provides important insight into what happened in our neighborhood's youth.

Scientists have found evidence that supports the Nice model's scattering era. Earlier this year, William Bottke of the Southwest Research Institute in Boulder, Colorado, and colleagues published an analysis of crater characteristics on the Moon's surface. Using an instrument aboard the Lunar Reconnaissance Orbiter that determines the depth of surface features, the team studied the Nectaris Basin floor, rim regions, and some of its ejecta. They chose this basin because it's thought to be the 12th youngest on the Moon and researchers often use it as a standard for measuring the endpoint of the Late Heavy Bombardment time frame.

Apollo astronauts brought back hundreds of pounds of lunar samples. Here, Harrison H. Schmitt, lunar module pilot, uses the "lunar rake" to collect rocks and rock chips ranging in size from 0.5 inch (1.3 centimeters) to 1 inch (2.5cm) during the Apollo 17 mission. NASA

The Nice model



The Nice model is planetary scientists' best theory of the early solar system's evolution. It maintains that around 4 billion years ago, Jupiter's and Saturn's orbits passed through a resonance, which restructured the solar system. Some astronomers say this change caused small rocky bodies to scatter, resulting in the intense pummeling of the inner solar system known as the Late Heavy Bombardment. *Astronomy*: Roen Kelly, after Gomes, et al.

Oberlin College/Bruce Simonson

Droplets of molten rock called spherules can tell scientists about the size and speed of the impactor that flash-heated the rock and created the spherules. Researchers have found four sites of these droplets on Earth that date to between 3.47 and 3.24 billion years ago.

An altered model

A team of four planetary scientists is working on a theory that revisits all of the parameters of the Moon's impact history. It — along with many planetary scientists — argues that there wasn't a severe "spike" in the number of lunar collisions 3.9 billion years ago, but instead a smoother increase, then decrease, in the impact number.

The Nice model (see "The Nice model," at left) is the best explanation scientists have so far of the early solar system. For this reason, Alessandro Morbidelli of the Observatoire de la Côte d'Azur in Nice, France; Simone Marchi and William Bottke of the Southwest Research Institute in Boulder, Colorado; and David Kring of the Lunar and Planetary Institute in Houston start with this simulation. According to Bottke, they explored what happens if the asteroid belt extended nearly to Mars. This question isn't just speculative; studies have found that the asteroid belt's current inner border is due to resonances with Jupiter's and Saturn's present-day orbits. In the past, however — when the gas giants' orbits were nearer to the Sun — the asteroid belt would have extended over a different range.

The researchers incorporated into the Nice model an extended region of the asteroid belt between 1.7 and 2.1 astronomical units (an astronomical unit is the average Sun-Earth distance); they call this new reservoir the "e-belt." The team found that the asteroids in this new area would slam into the inner solar system's worlds over a longer period of time, with the peak at 4.1 billion years ago. According to this "sawtooth" timeline, the number of collisions would then decline gradually until around 3.5 billion years ago.

The team finds that its model matches up with many observations — from the amount of large basins on the Moon to the number and time frame of vaporized rock-droplet layers on Earth. The researchers add, however, that this model fits the facts they understand now, but as is the way with science, that could (and likely will) change with new discoveries. — *L. K.*

Craters' sizes vary depending on the objects that created them, and Bottke's team observed that the impact craters near Nectaris were about 30 percent larger than those in more ancient regions. They attribute this size increase to faster-moving projectiles; a large change in the solar system — such as the restructuring of the giant planets' orbits — could increase the speed of smaller bodies.

Closer to home

But are there similar hints of a violent past on our planet? Earth's surface area and mass are much larger than the Moon's, so scientists expect that roughly 10 times as many bodies would have pummeled our planet during the Late Heavy Bombardment. While Earth's atmosphere and geological processes have weathered away most surface evidence of past impacts, some data hide below.

Incoming asteroids have huge amounts of energy due to their mass and high speeds. Thus, instead of digging out a trench in the material it hits, an asteroid explodes, vaporizing itself and the target rock. Once the vapor plume cools, it condenses into millimeter-sized droplets called spherules. These spherules fall to the ground, and the millimeter-to-centimeter-thick layer is preserved in rock. The key is to find if the age of one of these spherule layers — using a form of radiometric dating — aligns with the timing of the Late Heavy Bombardment.

Scientists know of 14 of these rock layers scattered across Earth, but none date to the theorized lunar cataclysm time period. Four, however, are from between 3.47 and 3.24 billion years ago, indicating perhaps a slow decline in collisions. "The impact cratering community has long recognized that there was an extended tail to the collisional processes occurring in the solar system," says David Kring of the Lunar and Planetary Institute in Houston.

Scientists also have dated spherule layers to some 2.5 billion years ago, which fits with another impact event in Earth's past — but far less intense than the Late Heavy Bombardment. Researchers are piecing together the impact history of the inner solar system, and this recent analysis of these spherules "provides a better dynamical framework for interpreting those [collision] events," says Kring.

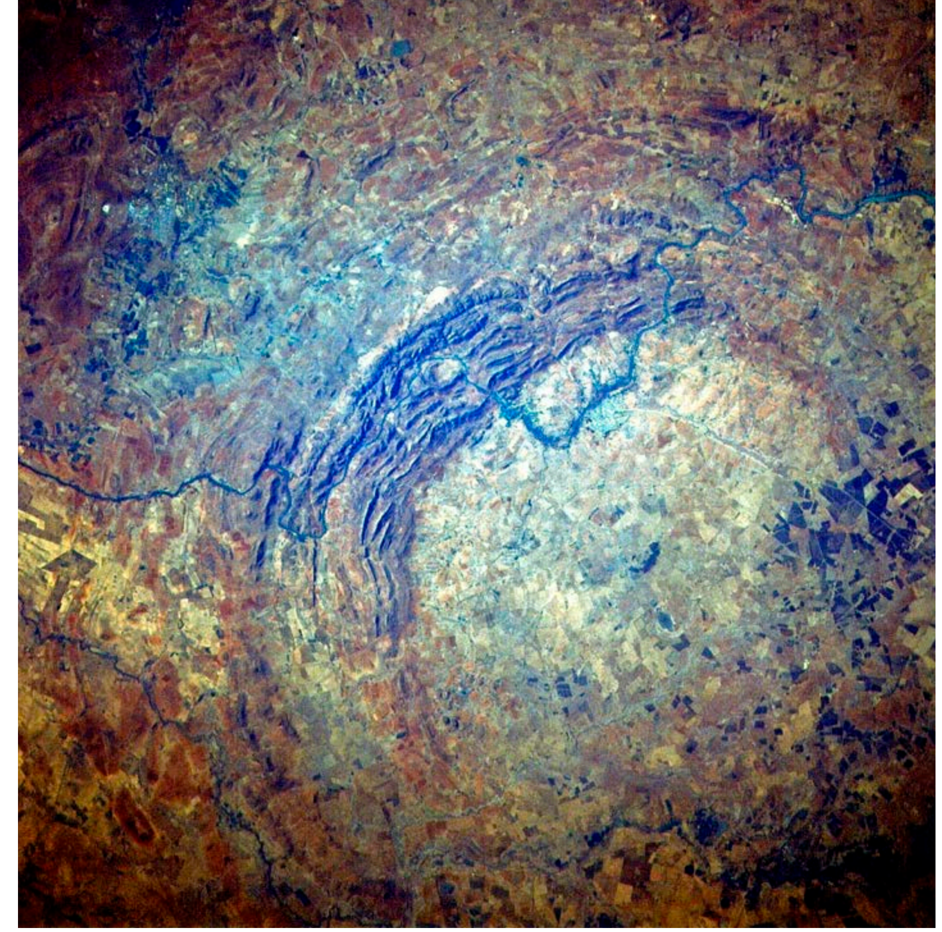
The state of the science

Scientists have been coming at the question about the bombardment spike's existence from every angle for decades. A number of researchers argue that just because the Apollo samples indicate a cratering event around 3.9 billion years ago, it doesn't mean there weren't impacts before that. Perhaps the rocks from these older impacts were pulverized by the younger collisions. "For example, we can't find many people on Earth today born before 1900, but lots of people born after that," explains Hartmann. "But it does not follow that a huge cataclysm wiped out all the earlier people around 1905. It merely means that people from before the cutoff did not survive till today."

Fast fact
In 2011, scientists discovered a 62-mile-wide (100 kilometers) crater in western Greenland that is Earth's oldest known impact site, with an age of 3 billion years.

More researchers believe that the pummeling time period lasted longer — perhaps up to 600 million years as opposed to a brief (on astronomical timescales) 100 million years. Bottke and colleagues have published a model that branches off the Nice model and traces a more gradual bombardment and decline (see "An altered model," page 34).

Even 40 years after Apollo astronauts finished gathering the first lunar samples and with the current refinements to the Late Heavy Bombardment theory, questions remain. "A lot of new dating and re-dating of lunar rock samples is being done by newer techniques," says Hartmann. This should help resolve the discrepancy between ages of the impact basins on our planet's satellite.



Vredefort Dome in South Africa marks the center of the third-oldest-known impact crater on Earth. It dates to about 2.02 billion years ago. NASA

Did the bombardment span just a hundred million years, or was it much longer? Was it a result of the giant planets shifting orbits? Was there a gradual decrease in the number of impacting objects? Researchers are using recent data from the Lunar Reconnaissance Orbiter to study details of the Moon's craters, they've found other ways to date the basins, and they've compiled a computational model to match the observations.

"We are still operating, however, in a data-poor environment, and we need samples from specific basins on the Moon to resolve the remaining questions," says Kring. One of those major impact sites is the South Pole-Aitken Basin, a target of a future lunar sample return mission.

"If you could go there, you could say something about the oldest impact," explains Bottke. And knowing the age of the oldest preserved lunar impact would be a key piece of information in figuring out the span of the Moon's (and the inner solar system's) bombardment history, and whether it was the short, intense cataclysm so many have theorized.

View the Nice model in action at www.Astronomy.com/toc.