Porosity of the moon's crust reveals bombardment history

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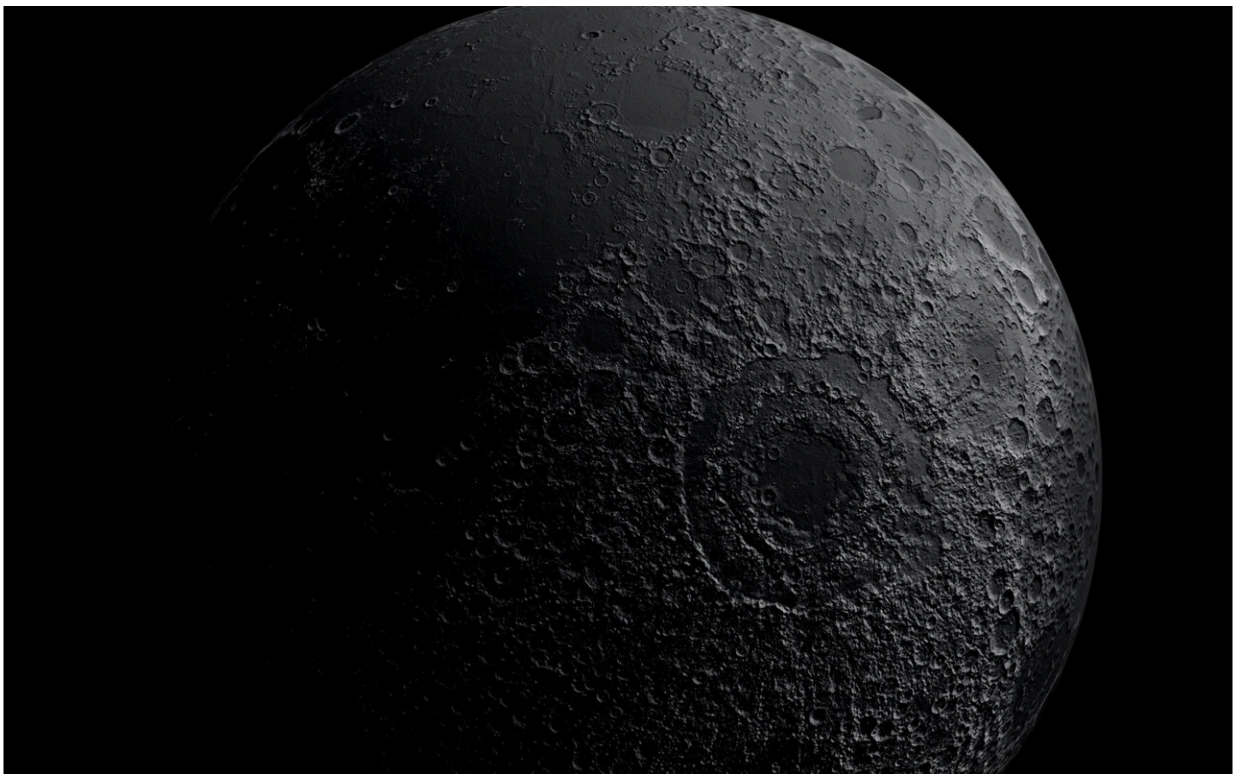

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Around 4.4 billion years ago, the early solar system resembled a game of space rock dodgeball, as massive asteroids and comets, and, later, smaller rocks and galactic debris pummeled the moon and other infant terrestrial bodies. This period ended around 3.8 billion years ago. On the moon, this tumultuous time left behind a heavily cratered face, and a cracked and porous crust.

Now MIT scientists have found that the porosity of the moon's crust, reaching well beneath the surface, can reveal a great deal about the moon's history of bombardment.

In a study appearing in *Nature Geoscience*, the team has shown through simulations that, early on in the bombardment period, the moon was highly porous—almost one-third as porous as pumice. This high porosity was likely a result of early, massive impacts that shattered much of the crust.

Scientists have assumed that a continuous onslaught of impacts would slowly build up porosity. But surprisingly, the team found that nearly all the moon's porosity formed rapidly with these massive imapcts, and that the continued onslaught by smaller impactors actually compacted its surface. These later, smaller impacts acted instead to squeeze and compact some of the moon's existing cracks and faults.

From their simulations, the researchers also estimated that the moon experienced double the number of impacts as can be seen on the surface. This estimate is lower than what others have assumed.

"Previous estimates put that number much higher, as many as 10 times the impacts as we see on the surface, and we're predicting there were fewer impacts," says study co-author Jason Soderblom, a research scientist in MIT's Department of Earth, Atmospheric and Planetary Sciences (EAPS). "That matters because that limits the total material that impactors like asteroids and comets brought to the moon and terrestrial bodies, and gives constraints on the formation and evolution of planets throughout the solar system."

The study's lead author is EAPS postdoc Ya Huei Huang, along with collaborators at Purdue University and Auburn University.

A porous record

In the team's new study, the researchers looked to trace the moon's changing porosity and use those changes below the surface to estimate the number of impacts that occurred on its surface.

"We know the moon was so bombarded that what we see on the surface is no longer a record of every impact the moon has ever had, because at some point, impacts were erasing previous impacts," Soderblom says. "What we're finding is that the way impacts created porosity in the crust is not destroyed, and that can give us a better constraint on the total number of impacts that the moon was subject to."

To trace the evolution of the moon's porosity, the team looked to measurements taken by NASA's Gravity Recovery and Interior Laboratory, or GRAIL, an MIT-designed mission that launched twin spacecraft around the moon to precisely map the surface gravity.

Researchers have converted the mission's gravity maps into detailed maps of the density of the moon's underlying crust. From these density maps, scientists have also been able to map the current-day porosity throughout the lunar crust. These maps show that regions surrounding the youngest craters are highly porous, while less porous regions surround older craters.

Crater chronology

In their new study, Huang, Soderblom and their colleagues looked to simulate how the moon's porosity changed as it was bombarded with first large and then smaller impacts. They included in their simulation the age, size, and location of the 77 largest craters on the moon's surface, along with GRAIL-derived estimates of each crater's current-day porosity. The simulation includes all known basins, from the oldest to the youngest impact basins on the moon, and span ages between 4.3 billion and 3.8 billion years old.

For their simulations, the team used the youngest craters with the highest current-day porosity as a starting point to represent the moon's initial porosity in the early stages of the lunar heavy bombardment. They reasoned that older craters that formed in the early stages would have started out highly porous but would have been exposed to further impacts over time that compacted and reduced their initial porosity. In contrast, younger craters, though they formed later on, would have experienced fewer if any subsequent impacts. Their underlying porosity would then be more representative of the moon's initial conditions.

"We use the youngest basin that we have on the moon, that hasn't been subject to too many impacts, and use that as a way to start as initial conditions," Huang explains. "We then use an equation to tune the number of impacts needed to get from that initial porosity to the more compacted, present-day porosity of the oldest basins."

The team studied the 77 craters in chronological order, based on their previously determined ages. For each crater, the team modeled the amount by which the underlying porosity changed compared to the initial porosity represented by the youngest crater. They assumed a bigger change in porosity was associated with a larger number of impacts, and used this correlation to estimate the number of impacts that would have generated each crater's current-day porosity.

These simulations showed a clear trend: At the start of the lunar heavy bombardment, 4.3 billion years ago, the crust was highly porous—about

20 percent (by comparison, the porosity of pumice is about 60 to 80 percent). Closer to 3.8 billion years ago, the crust became less porous, and remains at its current-day porosity of about 10 percent.

This shift in porosity is likely the result of smaller impactors acting to compact a fractured crust. Judging from this porosity shift, the researchers estimate that the moon experienced about double the number of small impacts as can be seen on its surface today.

"This puts an upper limit on the impact rates across the solar system," Soderblom says. "We also now have a new appreciation for how impacts govern porosity of terrestrial bodies."

More information: Ya Huang, Bombardment history of the Moon constrained by crustal porosity, *Nature Geoscience* (2022). DOI: 10.1038/s41561-022-00969-4.
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