have previously proposed that the body has a metabolic limit[2] of around 2.5 times BMR over extended periods, but it has never been properly tested until now, says Andrew Best, a biological anthropologist at Massachusetts College of Liberal Arts in North Adams and a co-author of the work.

Best and his colleagues recruited 14 high-endurance athletes — ultra-runners, cyclists and triathletes. Participants drank doubly labelled water containing deuterium and oxygen-18, which are heavy isotopes of hydrogen and oxygen. Once ingested, both deuterium and oxygen-18 will be lost from the body in the form of water, through urine and sweat. However, some of the oxygen-18 will also exit the body in the form of exhaled carbon dioxide.

By tracing the quantity of these molecules that were flushed out in urine, the scientists were able to calculate the amount of CO_2 exhaled, and, from this, estimate the number of calories the athletes burnt. This allowed the team to trace the athletes' energy output as they did activities — such as competitions — in real time, rather than measuring them on treadmills in a laboratory, says Best.

Hitting the ceiling

During multi-day competitions, some athletes burnt around 9,000 calories a day. But over longer periods — 30 and 52 weeks — their energy expenditure averaged about 2.4 times their BMR. The results show that even the most extreme athletes reach a metabolic ceiling that it is exceptionally difficult to exceed.

The researchers also found that, when athletes devoted more energy to running, cycling and swimming, they unconsciously cut back on using energy elsewhere, such as walking or fidgeting.

Nigel Turner, a metabolic researcher at the University of New South Wales in Sydney, Australia, says that using doubly labelled water, the gold-standard method for measuring energy expenditure, allowed the team to get accurate estimates of energy output on athletes' real activities. Doubly labelled water has only recently become affordable, Best says, making the study possible.

Turner says one factor that probably limits prolonged exertion is nutrient intake, because that also requires energy. Past research has suggested that humans can only metabolize the caloric equivalent of about 2.5 times their BMR[3].

"If energy expenditure exceeds 2.5 times BMR for a prolonged period, the energy intake of athletes wouldn't be able to keep up and they would have to start using body stores, which could include muscle breakdown," Turner says. "This would, in turn, potentially compromise performance."

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2. Westerterp, K. R. *J. Exp. Biol.* **204**, 3183–3187 (2001).
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SURPRISE METEORITE DEBRIS UNCOVERED ON MOON'S FAR SIDE

The rare samples, uncovered by China's Chang'e-6 mission, might help to reveal secrets of how the Solar System evolved.

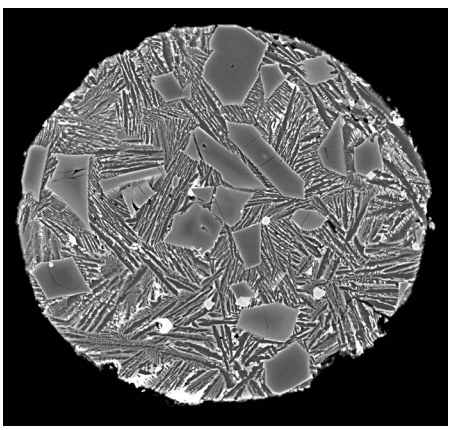
By Jenna Ahart

Sifting through the first-ever rock samples collected from the far side of the Moon, scientists in China have unearthed a surprise: fragments of a rare type of meteorite that could help to piece together the Solar System's history. The debris — scooped up by China's Chang'e-6 mission and returned to Earth in June last year — resembles material from asteroids that carry dust pre-dating the Solar System. Studying the chemical composition of this debris could help to trace how asteroids seeded planetary bodies such as Earth and the Moon with volatile compounds, including water.

"The Chang'e-6 mission has a list of major questions to answer, but this wasn't even on that list," says Yuqi Qian, an Earth and planetary scientist at the University of Hong Kong, who was not involved in analysing the fragments. "It's such an unexpected and important finding." The authors reported their discovery last week (J. Wang *et al. Proc. Natl. Acad. Sci. USA* **122**, e2501614122; 2025).

Near and far

Most missions that have returned rocks from the Moon have sampled the surface facing Earth — the near side — which has fewer craters and has hosted greater volcanic activity. Chang'e-6, however, landed on the far side, at the Moon's largest, deepest crater — the South Pole–Aitken Basin, which accounts for about one-quarter of the Moon's surface area. One of the main objectives was to better understand why the far side looks so different from the near side.



YI-GANG XU

Meteorite fragment discovered on Moon.

Another was to explore the huge basin, which scientists think was created when an asteroid smashed into the Moon about four billion years ago. The crater is probably rich with fragments from that and other asteroid impacts, alongside rock from the lunar mantle — the layer beneath the crust — dredged up by the collisions.

But the discovery of the rare meteorite fragments was a surprise. At first, the researchers thought the samples came from the Moon's mantle. But after analysing the iron, manganese and zinc levels in the debris, they found a mismatch with other lunar materials, indicating they were not from the Moon itself. So, the team examined the relative levels of three oxygen isotopes in the samples; these ratios are "like human fingerprints" and can tell you what type of planetary body the debris comes from, says Mang Lin, an author of the paper and geochemist at the Chinese Academy of Sciences's Guangzhou Institute of Geochemistry (GIG). "This approach is basically space forensics."

The isotope signature closely matched that of two rocky asteroids already studied by humans, named Ryugu and Bennu. NASA grabbed samples from Bennu in 2020, and the Japanese space agency collected fragments of Ryugu in 2019. Both asteroids held dust grains pre-dating the Solar System, as well as elusive volatile compounds such as water.

Analysis of the new fragments seems to confirm that this type of asteroid delivered a significant supply of water and other compounds to the Moon. By further studying the chemical composition of the samples, scientists might be able to zero in on what part such space rocks played in the development of Earth and the Moon. This type of meteorite rarely survives when it hits Earth, so samples are rare, says co-author Jintuan Wang, a geosciences researcher also at GIG.

Team leader Yi-Gang Xu, also at GIG, thinks that by studying more Chang'e-6 samples, the group might pinpoint the age of such meteorite fragments, which would help to determine whether their parent asteroid created the South Pole–Aitken Basin.