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SCIENCE NEWS BY AGU

Gaining New Insights from Old Storms

South America Is Drying Up

Earth May Survive the Sun’s Demise

HOW GREAT WAS the Great Oxidation Event?

Answers to existential questions are coming from a planetary perturbation billions of years in the past.

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the evolution of a new form of single-celled organisms that could photosynthesize, he said. "You finally get life on the planet, and then what happens? It evolves to produce oxygen and kills off almost everything."

"Unlocking oxygen allowed life to become more complex...that's why we're here."

"These huge perturbations cause life to go in retrograde—they cause conditions to get worse," he said. He added that Earth's ecosystems tend to show that "diversity comes about when you have long periods of stability." For example, coral reefs tend to be more diverse if they've had a long period of stability during which to evolve.

Nicholson had a different view: "Unlocking oxygen allowed life to become more complex...that's why we're here," she said. "If you were a microbe [during the Great Oxidation Event], that would have been really bad. But in order for a biome to increase in complexity, that's going to have to involve some kind of upheaval to life."

The idea that life eventually destroys itself by spurring its own extinction events contradicts the findings of the authors' modeling experiments, which show stability arising from living systems over time even with large-scale perturbations, Mayne said. "Our idealized work does run against the Medea hypothesis," he added. "Our modeling suggests that statistically, biospheres build complexity and are not self-destructive."

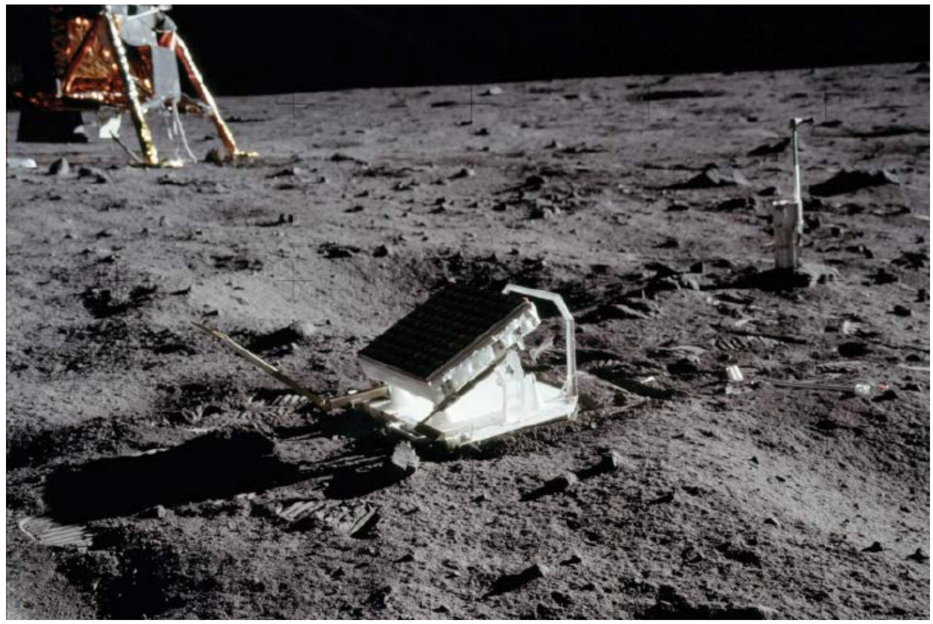
Gaias Beyond Earth

The new research could help scientists narrow their search for extraterrestrial life, according to the authors.

For example, planets near the edges of the habitable zone—the window of distance from a planet's star that allows for the existence of liquid water—may be more likely to have experienced perturbations to their climates, which could have spurred more complex life. Orbital shifts and asteroid impacts could similarly perturb a planet.

By **Grace van Deelen** (@GVD__), Staff Writer

The Relatively Messy Problem with Lunar Clocks



Apollo 11 astronauts placed the Laser Ranging Retroreflector on the surface of the Moon. This device was designed to test Einstein's theory of general relativity, which is necessary to understanding the different rates at which clocks run on the Moon versus Earth. Credit: NASA; scan by NASA Johnson

What time is it on the Moon?

In April 2024, the White House issued a challenge to scientists to establish a lunar time standard, looking ahead to increased international presence on the Moon and potential human bases as part of NASA's Artemis initiative.

The real question isn't "What time is it?" but, rather, "How quickly does time pass?"

The time that a clock reads can be set by any timekeeper, but physics determines how quickly time passes. In the early years of the 20th century, Albert Einstein theorized that two observers won't agree on how long an hour is if they aren't moving at the same speed in the same direction. That disagreement also holds between a person on Earth's surface and another in orbit or on the Moon.

"If we are on the Moon, clocks are going to tick differently [than on Earth]," said theoretical physicist Bijunath Patla of the National Institute of Standards and Technology (NIST) in Boulder, Colo. He noted that the Moon's motion relative to ours should make clocks run slower than Earth standard, but its lower gravity leads to clocks running faster.

"So these are two competing effects, and the net result of this is a 56-microseconds-per-day drift," he said. (That's 0.000056 second.)

Patla and his NIST physicist colleague Neil Ashby used Einstein's theory of general relativity to calculate this number, an improvement over previous analyses. They published their results in the *Astronomical Journal* (bit.ly/Moon-clocks).

Though a 56-microsecond difference is small by human standards, it's significant when it comes to guiding multiple missions with pinpoint accuracy or communicating between Earth and the Moon.

"The fundamental thing is safety of navigation in the context of a lunar ecosystem when you have lots more activity on the Moon than you have now," said Cheryl Gramling, a systems engineer at NASA's Goddard Space Flight Center. "When it comes to navigation, a drift of 56 microseconds over a day between a clock on the Moon and [a clock] on Earth is a big difference, so you have to accommodate that."

Modern precision navigation relies on synchronizing clocks. This involves coordination using radio waves, which travel at the speed of light. Gramling noted that light travels 30 centimeters (11.8 inches) in 1 nanosecond (0.001 microsecond)—an unbelievably short amount of time by human standards—so failing to account for the 56-microsecond discrepancy could potentially result in navigational errors as large as 17 kilometers per day. Even a fraction of that is unacceptable when it comes to Artemis missions, which will require knowing the position of every rover, lander, or astronaut to within 10 meters at all times.

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Free Falling

A key result of the theory of relativity is that there's no such thing as absolute time. A clock on Earth's surface will tick more slowly than one in orbit because of gravitational effects, which is why GPS satellites have to take relativity into account. (Coordinated universal time and other standards on Earth use networks of clocks that correct for tiny gravitational differences at various elevations, too.)

Determining the difference in timekeeping between Earth and the Moon adds extra complications. The Moon is moving relative to any spot on Earth's surface because of our rotation and its orbit around us, which means any lunar clock will appear to run slower from our point of view. In addition, any clock on the Moon is affected by the Moon's gravity and Earth's. (Artificial satellites aren't large or massive enough for their own gravitational effects to matter.)

Properly handling these effects of relativity requires picking an appropriate frame of reference. Ashby and Patla tackled the problem by acknowledging that the Earth-Moon system is in free fall—moving only under the influence of the Sun's gravity—with each orbiting their mutual center of mass. That enabled them to formulate the contributions from each complication: the rotation of each body, tidal forces, deviations in shape from perfect spheres, and so forth.

Ashby and Patla also performed the calculation for gravitationally stable positions in orbit between Earth and the Moon known as Lagrange points, which could be used for communications relay satellites.

Meanwhile, theoretical physicist Sergei Kopeikin of the University of Missouri and astronomer George Kaplan of the U.S. Naval Observatory independently calculated a 56-microsecond time shift between Earth and the Moon (bit.ly/lunar-time). They also calculated smaller, periodic fluctuations in clock rates due to tiny tidal force variations from the Sun and Jupiter, nanosecond-level effects that, nevertheless, need to be accounted for to obtain 10-meter-scale or better navigational precision.

"The [relativity] community has done us a great service by publishing all this work."

"The [relativity] community has done us a great service by publishing all this work," Gramling said. "Now we have something to bring to the whole international community of timing experts and say, 'Is this the model that we can standardize for the Moon?'"

It will be many years or decades before the Moon is populated with enough people and robots to need this level of timekeeping. However, scientists and engineers recognize how important it is to have a lunar standard time in place long before it's necessary. Now they have taken that difficult first step toward knowing what time it is on the Moon.

By **Matthew R. Francis,** Science Writer