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LIFE ON AN EXOPLANET?

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Lunar labs

The time is ripe to start building groundbreaking astronomical observatories on the moon, says **Rebecca Boyle**

WHEN Michael Collins floated above the far side of the moon during the Apollo 11 mission in 1969, he knew he would be remembered as the loneliest human in history. He recalled feeling unafraid, almost exultant, thinking about everything on the other side of the moon: Neil Armstrong and Buzz Aldrin on the lunar surface and, beyond that, every creature on Earth and everything humanity had ever built. On his side, as Collins wrote in his memoir, was "one plus God only knows what".

A half-century later, the famously empty lunar landscape is starting to get busier. Not only are NASA and other space agencies preparing to send humans to the moon for longer periods of time, researchers around the world are working on blueprints to turn it into the most powerful astrophysics laboratory in history. This could address the deepest questions we have ever asked. How did the first stars ignite? Why has the universe evolved the way it did? Is there anyone else out there?

"On the moon, we can think about concepts that, here on Earth, are completely impossible to realise," says Jan Harms, an astronomer at the Gran Sasso Science Institute in Italy. The conditions there seem nearly purpose-built to house cutting-edge observatories that could answer some of the most perplexing questions about the cosmos. The moon's unique peace and quiet, especially on the side that never faces Earth, could make it a portal to the history of the universe, from the first galaxies to the mysterious dark energy that stretches the universe apart at an ever-accelerating rate. But first, we have to build the observatories.

"It was silly to think about this 10 years ago, even. There was no real, believable path to having large equipment placed on the moon, so essentially every astronomer, including me, dismissed the idea," says Martin Elvis at the Harvard-Smithsonian Center for Astrophysics in Massachusetts. "Now, it's worth thinking about. And once astronomers start thinking, they are very creative." Some of those creative ideas are starting to become reality.

One of the most audacious involves placing a radio telescope on the far side of the moon – the quietest place in the solar system. Human technology has been spewing out radio signals for more than 100 years, and the far side is the only place they can't reach. That means it may be the only location in the solar system where the weak radio waves from throughout the cosmos aren't drowned out.

Lighting the dark ages

Radio waves are a key tool for measuring faint and very distant cosmic objects. We can see faraway stars and galaxies in all wavelengths of light, but only in radio waves can we "see" the universe before there was any light at all. Cosmologists want to understand this epoch before the first stars, called the cosmic dark ages, because it set the course for all that was to come, including where and why galaxies formed. To study it, we must look for particles of light, or photons, ejected from the first hydrogen atoms, formed about 380,000 years after the big bang.

"That is the only way of doing it. You have no other information for cosmology," says Nivedita Mahesh, an astronomer at the California Institute of Technology.

The problem is, these first photons can only be spotted in the form of low-frequency radio waves – the same frequencies as FM radio on Earth. Observing them from our planet is all but impossible, because they reflect off the atmosphere, but the far side of the moon could be the perfect vantage point. By studying the distribution of the photons emitted by those early hydrogen atoms, astronomers can potentially build a map of the cosmic dark ages.

A far-side radio telescope could even study the auroras and magnetic fields of distant exoplanets, the signals from which would be absorbed by Earth's atmosphere and drowned out by our own noise. This could help us understand how an alien planet – and any life on it – would be affected by its star. "Then it's a very profound question it can answer," says Mahesh. "If an exoplanet has a magnetic field, is it protecting that planet from incoming stellar flares? [If so], it could be a nice planet to follow up, to look for signs of life."

The moon would also be the best place to go to improve the viewing power of the Event Horizon Telescope (EHT), the network of radio telescopes that took the first images of black holes. Better black hole imaging could help astrophysicists understand these strange cosmic denizens and test theories of gravity. Extending radio observations to the lunar surface and linking them with Earth-based telescopes would turn the EHT into a monstrously powerful observatory.

The work towards these goals has already begun. The first lunar radio astronomy experiment, NASA's Radio wave Observation at the Lunar Surface of the photoElectron Sheath (ROLSES-1), landed last year on the near side of the moon, close to its south pole, aboard a craft made by private company Intuitive Machines. The lander tipped over shortly after touching down, limiting its lifespan and the data gathered. But the team was nevertheless able to collect some radio waves from Earth and ›

ALLAN SANDERS

Jupiter. As a demonstration, the experiment succeeded, showing that a small instrument on the moon can indeed detect radio waves. Now, scientists are clamouring for more.

The next lunar radio experiment is set to be NASA's Lunar Surface Electromagnetics Experiment, LuSEE-Night, which is scheduled to launch for the far side of the moon in 2026. Its radio receivers will measure low-frequency light from our galaxy, taking a small step towards studying the faraway photons from the first hydrogen atoms. Once astronomers understand the "white noise" of the galaxy, they can figure out how to separate the signals necessary for cosmology experiments.

NASA engineers are also working on the proposed Lunar Crater Radio Telescope, which would be a large antenna inside a crater on the far side of the moon. It is still in the planning stages, but some designs call for a fleet of wall-climbing robots to be sent to a large crater. After landing, the robots would string wires across the crater rim, constructing a spiderweb-like mesh antenna. A radio receiver would then be suspended from the antenna's centre. Though the proposed diameter varies from 350 metres to a kilometre, even a lunar crater telescope at the bottom end of this range would still be among the largest radio receivers ever built.

Ripples in space-time

The moon could also be used to investigate gravitational waves, the shuddering of space-time itself in the wake of gargantuan collisions. Adding these ripples in space-time to more traditional, light-based observations is like gaining a whole new astronomical sense, like being able to hear as well as see.

So far, astronomers on Earth have caught the reverberations of merging binary black holes and neutron stars. But future observations could yield even more information about the nature of cosmic objects and gravity itself. The problem is Earth – a seismically active world with moving tectonic plates, not to mention wind, water, tides, elephant herds and humans. The lasers that detect gravitational waves in the Laser Interferometer Gravitational-Wave Observatory (LIGO) must cancel out all that Earthly noise, and be supercooled and kept in a vacuum to boot. But on the moon, there is minimal seismic activity, no water or wind, no elephants and no human presence, at least not yet. Plus, the pressure there is only 10 times higher than that in LIGO's carefully evacuated laser tubes. The entire project would be much easier to construct and use, says Harms.

"Even with the same concept as LIGO, we could extend to lower frequencies and see sources LIGO could not see, such as larger-mass black hole binaries. That would be really a new science you could do with a [lunar detector]," says Harms. "And once you have a detector like LIGO on the moon, then you could essentially let them observe together."

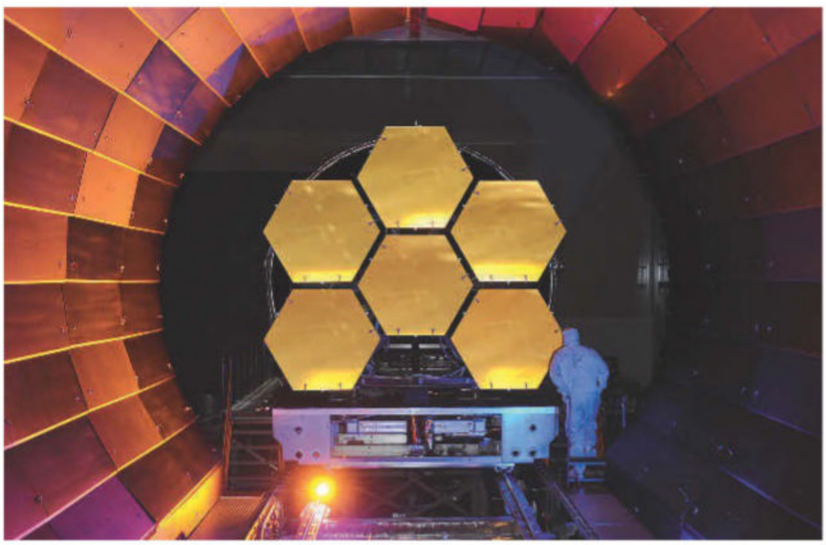
The power of interferometers like LIGO comes from having multiple detectors that work together as a single, enormous instrument – the further apart they are, the more powerful the overall observatory. With such a huge distance between observing stations on Earth and the moon, astronomers would be able to anticipate a gravitational wave's arrival and point optical, infrared and X-ray observatories at the source, says Harms.

Detecting gravitational waves from a moon-based detector would also enable astronomers to study different exotic objects, says Jasmine Gill at the Harvard-Smithsonian Center for Astrophysics. The moon could help us see the cores of collapsing supernovae and better understand how these exploding stars become neutron stars or black holes.

"We still can't catch those final moments of collapse or the final moments afterward," says Gill. There is simply too much noise on Earth, and it is too unpredictable. "But if you head to the moon, you are able to do it," she says.

"The moon could help us see the cores of collapsing supernovae"

The moon could host telescopes bigger than JWST (pictured being built below)



BALL AEROSPACE

INTUITIVE MACHINES

An artist's impression of the lander carrying ROLSES-1, the first radio telescope on the moon

Work is already under way on the Laser Interferometer Lunar Antenna, a proposed LIGO-like observatory on the moon. In the current concept, three landers would settle on the edge of a large crater, a few kilometres from one other. Each would hold lasers, mirrors and a vibration-isolation system to cancel out any lunar quakes – a simple enough set-up that it could be launched in the next decade, according to the team behind it at Vanderbilt University in Tennessee.

Other lunar development could be a problem for this proposal, though. Exploration of the moon has ramped up over the past decade and space agencies have various plans for long-term settlements and increased activity there. Although still a long way off, any lunar age of industry could be accompanied by some of the Earthly conditions that astronomers want to go to the moon to escape. "Once we start mining or building railroads, we are immediately going to kill that pristine environment," says Gill. "But we can just boost up the laser power and make sure our detectors still work well." Upgrades similar to those regularly performed on LIGO's instruments, along with maintenance, would require astronauts to visit the detector regularly, she says – but there may be a simpler way.

The Lunar Gravitational-wave Antenna (LGWA) is a European Space Agency project that aims to use the moon itself as a detector by measuring gravitational waves passing through its entire bulk. Near the moon's poles, sunlight streams onto the surface at extreme angles, so some crater floors never see the light of day and stay at a temperature of -246°C or even lower. The extreme cold and low pressure would make it easier to catch a passing gravitational wave. By installing a set of simple vibration sensors in one of these permanently shadowed craters, the LGWA might be able to observe gravitational waves from objects and phenomena that are too faint to spot from Earth, such as the very first black holes.

The idea even has precedent: Apollo 17, which landed on the moon in 1972, carried a prototype gravitational wave experiment called the Lunar Surface Gravimeter. In the end, it didn't work properly, but designing something similar with greater sensitivity wouldn't be hard, says Harms. "Apollo 17 did the tough part," he says. "Now we have to repeat it."

The moon is also a prime location for more traditional astronomy. Over the past few years, the international astronomy community has been agog over images from the James Webb Space Telescope (JWST), which are revolutionising our understanding of cosmic history. The moon's natural craters could provide a cosy home for an even more powerful infrared observatory.

The biggest telescope

Jean-Pierre Maillard at the Paris Institute of Astrophysics is leading an effort to conceive of an infrared telescope in a dark lunar crater, which would keep it as cold as required. Such craters naturally have a circular, concave shape that is just right for a telescope. Power could be supplied from the crater's rim, where the sun always shines along ridges known as peaks of eternal light. And the moon's weak gravity could make it possible to deploy a truly colossal mirror – impossible on Earth because the planet's gravity would warp the mirror's glass. On the moon, "a lot of problems go away", says Elvis. Maillard's work has shown that a huge infrared telescope on the moon could be more sensitive than any of the similar observatories we have ever built before, on the ground or in space.

But more than the other proposals, an infrared telescope would have one major issue to contend with: lunar dust. Many scientists and even geologists don't fully appreciate how difficult moon dust can be to deal with, says Mihály Horányi, a physicist at the University of Colorado Boulder.

After walking on the surface of the moon during Apollo 11, Aldrin and Armstrong rejoined Collins absolutely coated in dust. Its electrostatic charge made it impossible to brush off. After two or three moonwalks, the astronauts on all the Apollo missions were so thoroughly dusty that further outings could have threatened their lives – dust caked in every buckle and latch of their suits and landers could have prevented perfect seals, causing air leaks. Future missions have to consider this pervasive threat, too, says Horányi. After all, what good will a perfect, concave telescope mirror be if it turns into a giant, dust-collecting cup?

Dust on the moon levitates at lunar sunrise and sunset, for reasons scientists don't totally understand, and this behaviour could also interfere with sensitive gravitational wave-detecting lasers or even radio instruments. Horányi and others are hoping for missions to study moon dust and its strange behaviour before anyone builds a lunar observatory.

Beyond dust, future astrophysics outposts will also have to contend with intense cosmic radiation, along with dramatic temperature differences between lunar day and night. LuSEE-Night gets the latter part of its name from this effort: it will be one of the first spacecraft built to withstand the two-week-long lunar night.

A lot has changed since Collins was the only human on the moon's far side. The lunar surface now teems with landers and rovers, and they could soon be joined by telescopes, gravitational wave detectors and radio dishes. The question isn't whether this will happen, but when.

"There will be a human presence on the moon in a decade or less," says Richard Green at the University of Arizona, who chairs the International Astronomical Union's working group on moon-based astronomy. In the meantime, scientists need to start thinking about areas they want to reserve for future research. "We aspire, in the next year or less, to have a list of actual physical sites that we think should be candidates for exploration for astronomy," says Green.

Future lunar orbiters might glimpse a surface criss-crossed by power lines, dotted with radio antennae tuned to the distant beginnings of our cosmos and inky black craters full of infrared sensors soaking up far-flung starlight. These new projects may finally help us answer the same question Collins posed to himself as he floated alone above the moon: what else is out there? ▮

Rebecca Boyle is a science journalist based in Colorado. She is the author of *Our Moon*, a history of humanity's relationship with Earth's satellite