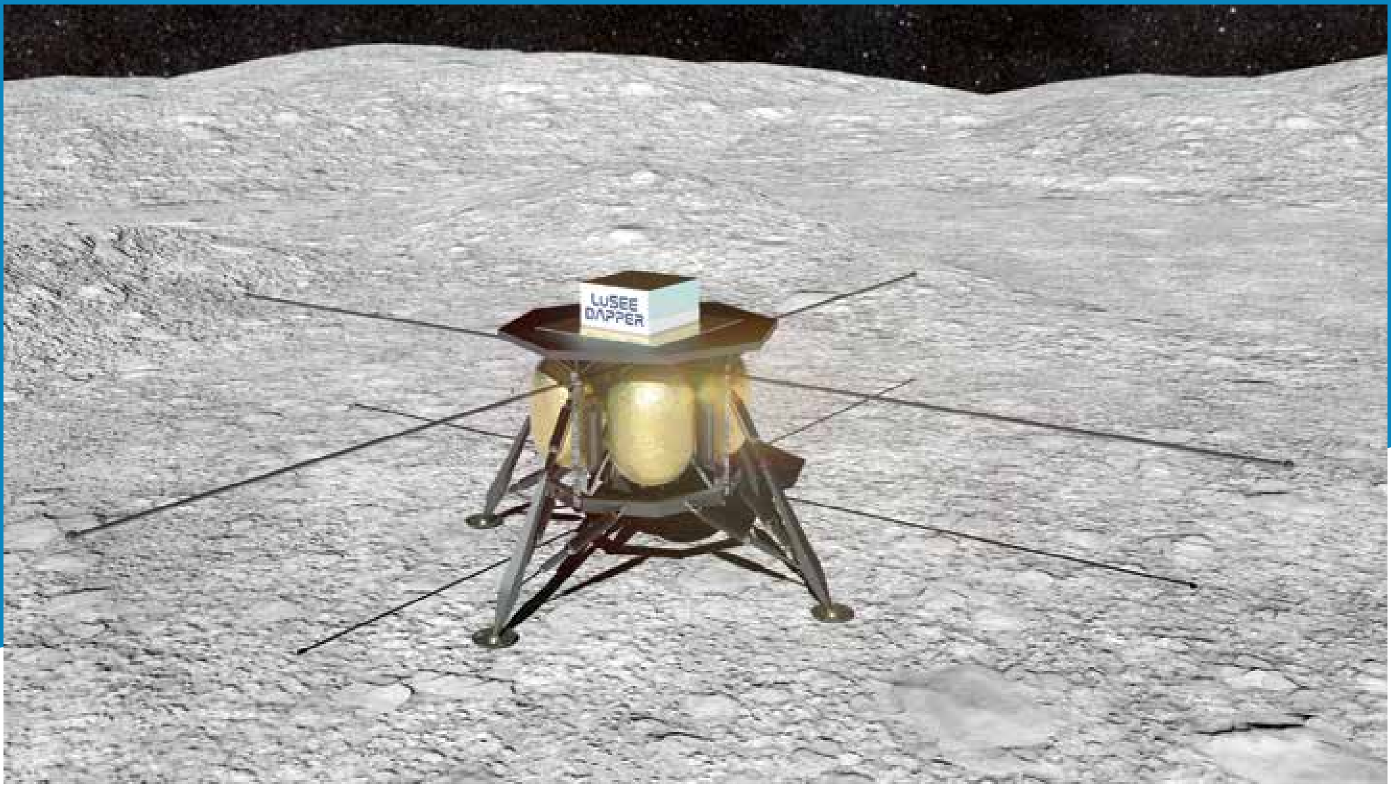

The Lunar Frontier

By the late 2020s, we may have deployed multiple radio astronomy instruments on Earth's natural satellite.

▲ **COSMIC EXPLORER** From the Moon's farside, NASA's DAPPER will look for faint radio signals from the early universe.

Radio wavelengths give astronomers access to an unseen universe, from stellar flares to jets launched from supermassive black holes. But arguably, we have yet to take advantage of the best place in the inner solar system for low-frequency radio astronomy: the Moon.

The lunar farside always faces away from Earth and is thus radio-quiet, shielded by the Moon itself from radio-frequency interference coming from powerful Earth-based transmitters. The Moon also lacks a substantial ionosphere, whereas Earth's ionosphere absorbs and refracts cosmic radio sources. Furthermore, the lunar environment is dry and stable, leading to steadier radio observations.

Radio astronomy from the Moon is not a new idea — astronomers proposed a lunar radio observatory at a science symposium in 1965, before Apollo 11. In a separate endeavor, NASA's Radio Astronomy Explorer 2 orbited the Moon from 1973 to 1975, the first mission to gather radio data above the farside. It confirmed the radio-quiet environment and made low-frequency measurements of Jovian radio bursts and sources in the Milky Way.

But lack of access to the Moon meant that the next lunar radio mission didn't occur until 2018, when China launched its Chang'e 4 mission. After touching down on the lunar farside, the lander unfolded three 5-meter radio booms; another three 5-meter antennas, part of the Netherlands-China Low-frequency Explorer, orbit the Moon aboard the Queqiao satellite, which acts as a communications relay for the lander and rover.

As nations reestablish access, the Moon is open again to science and exploration. Using new rockets and technologies, spacecraft from China, the U.S., India, and Japan are surveying the Moon for water and other resources and assessing its potential as a platform for astrophysics. NASA's Commercial Lunar Payload Services (CLPS) program is to begin delivering science instruments on robotic landers starting in 2022. The public-private partnerships behind these missions have dramatically reduced their costs.

In recent years, several exciting science cases for farside radio telescopes have emerged. For example, low-frequency (below the FM band) observations of nearby exoplanet systems enable us to investigate stellar winds and planetary

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magnetic fields, which affect potential habitability.

Meanwhile in cosmology, emission from neutral hydrogen in the early universe shifts into the low-frequency range as the photons traverse the expanding universe. These signals probe the dark ages of the universe's first few hundred million years, as well as the cosmic dawn when the first stars were born. Early-universe investigations will rigorously test the standard model of cosmology and may uncover new exotic physics involving dark matter, dark energy, and cosmic inflation (*S&T:* June 2019, p. 22).

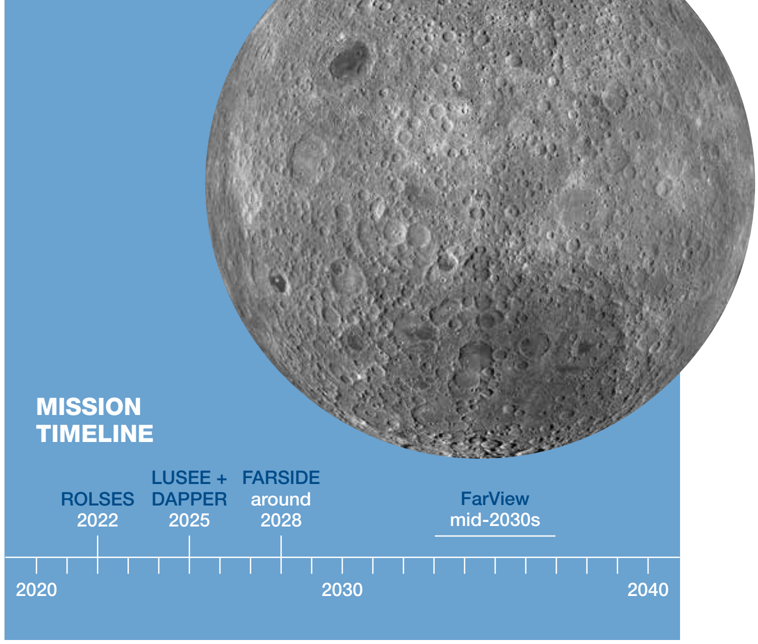
Several U.S. missions to the Moon — both nearside and farside — are in the works. Intuitive Machines plans to place its NOVA-C lander on the lunar nearside in early 2022. This CLPS mission includes the ROLSES (Radio Wave Observations at the Lunar Surface of the Photoelectron Sheath) instrument, using simple single antennas. LUSEE (Lunar Surface Electromagnetics Experiment) will follow in 2025 and will land in Schrödinger Basin on the farside. Both radio instruments will investigate the thin, ionized plasma created when the solar wind slams into the lunar surface, as well as the charged dust and radio waves that come from solar eruptions.

I myself am involved with several endeavors. Stuart Bale (University of California, Berkeley), Richard Bradley (National Radio Astronomy Observatory), and I recently proposed that the Dark Ages Polarimeter Pathfinder (DAPPER) could fly with LUSEE to the lunar farside. The additional antennas and receiver on DAPPER would enable investigations of the low-frequency radio spectrum up to 110 MHz. Absorption troughs in this frequency range will reveal not only when the first stars and galaxies "turned on" but also what they looked like, including their typical masses and luminosities.

Together with Gregg Hallinan (Caltech) and my colleagues at the Jet Propulsion Laboratory, I have also proposed FARSIDE (Farside Array for Radio Science Investigations of the Dark Ages and Exoplanets), which would consist of 256 dipole antennas working together to act as a single, large radio antenna on the lunar surface. The mission could be ready for flight later this decade.

The NASA Innovative Advanced Concepts Program also recently funded the study of a 100,000-antenna array called FarView. These antennas, which would be manufactured onsite from lunar regolith, would map fluctuations in neutral hydrogen in the early universe, providing insights into the nature of the cosmic web, dark matter, and primordial gravitational waves. Ronald Polidan and Alex Ignatiev (Lunar Resources, Inc.) and I are proposing to place FarView on the Moon in the 2030s.

This ambitious road map for lunar radio astronomy, combined with renewed access to the Moon, will open a new window to the low-frequency cosmos.



THE FARSIDE The FARSIDE lander would carry more than 200 radio antennas, strung together and deployed using four small, wheeled rovers.

TIMELINE: TERRI DUBÉ / *S&T*; MOON: NASA GSFC / ARIZONA STATE UNIVERSITY; LANDER: BLUE ORIGIN

JACK BURNS is a professor of astrophysics and physics at the University of Colorado, Boulder. He served on the Presidential Transition Team for NASA in 2016–17, helping to define NASA's new missions to the Moon — including low-frequency astrophysics from the lunar farside as well as what is now Project Artemis.

FURTHER READING: Burns, J.O., et al. "Low Radio Frequency Observations from the Moon Enabled by NASA Landed Payload Missions." *Planetary Science Journal* 2021.