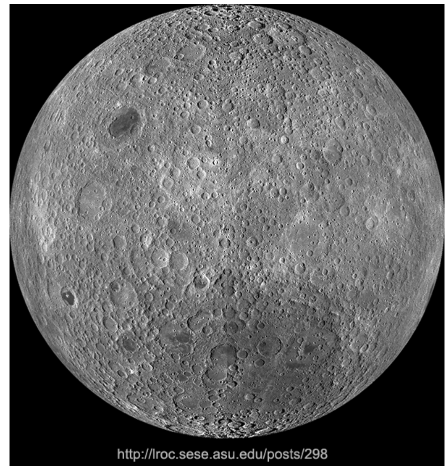
Headline Article

May 3, 2021



Seeing What We Have Never Seen Before: Low-Frequency Radio Astronomy from the Moon

--- Low-frequency radio observations from the radio-quiet lunar farside will allow astronomers to probe the universe from its mysterious dark ages after the Big Bang, to the nature of the magnetospheres of planets around other stars and the outer planets in our Solar System, and to better understand the causes of explosive release of plasma from the Sun's corona.

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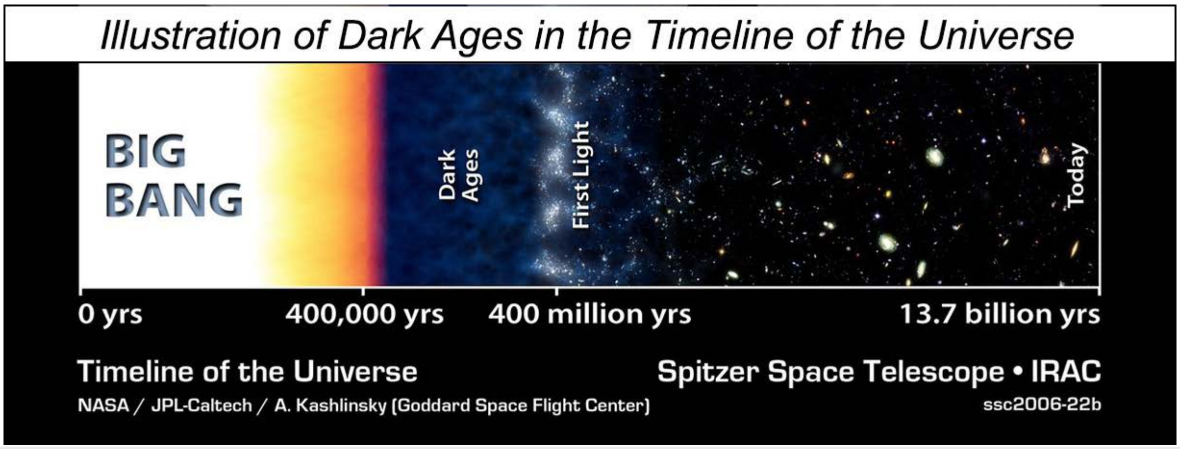
Jack O. Burns and teammates at the Center for Astrophysics & Space Astronomy at the University of Colorado, Boulder, NASA Goddard Space Flight Center, the University of California at Berkeley, Caltech, and the University of Michigan have bold plans to address profound questions about the cosmos. They focus on low-frequency radio observations, a region of the electromagnetic spectrum that is troublesome for Earth-based radio observatories because of human-produced radio frequency interference (RFI) combined with atmospheric and ionospheric sources of noise. Burns and colleagues propose sending a series of missions to the lunar farside (which never faces the Earth), a significant portion of which is shielded from the troublesome terrestrial noise. Their goal is to install an array of 128 pairs of antenna nodes on the lunar farside distributed over a spiral 10 kilometers in diameter. This large radio telescope, not bathed in radio noise from Earth, will be able to measure fluctuations in the 21-cm (1420 MegaHertz, MHz) line derived from neutral hydrogen. The measurements will allow astrophysicists to probe a time called the Dark Ages when there were no stars or galaxies in the expanding universe. Measurements of the 21-cm emissions are critical to probing astonishing features such as inflation of the universe, the formation of the first stars and first Black Holes, and the non-standard physics of dark matter. Lunar low-frequency telescopes of more modest dimensions also have other fascinating targets such as studying magnetospheres around the other planets and even in other solar systems, and understanding the behavior of the Sun, our local star. The more modest missions will be trailblazers for the ambitious farside array, and human and robotic missions will build up the infrastructure needed for construction, operation, and repair of advanced radio telescope facilities on the Moon.

References:

- Burns, J. O. (2020) Transformative science from the lunar farside: Observations of the dark ages and exoplanetary systems at low radio frequencies, *Philosophical Transactions of the Royal Society A,*, 379:20190564, doi: 10.1098/rsta.2019.0564. [**article**]
- Burns, J. O., MacDowall, R., Bale, S., Hallinan, G., Bassett, N., and Hegedus, A. (2021) Low radio frequency observations from the Moon enabled by NASA landed payload missions, *The Planetary Science Journal,* 2:44, doi: 10.3847/PSJ/abdfc3. [**open access article**]
- **PSRDpresents:** Seeing What We Have Never Seen Before: Low-Frequency Radio Astronomy from the Moon --**Slide Summary** (with accompanying notes).

Low Frequency Radio Waves and High Value Science

Astronomers (also called cosmologists) who study the origin and evolution of the universe, including its mind-bending space-time relations, have a mostly satisfying story about origin and evolution of the universe. A Cliff Notes version is summarized in the illustration below. By about 400,000 years after the Big Bang (which happened somewhere around 13.8 billion years ago) the originally hot universe had expanded (astronomers call this inflation) and cooled enough to precipitate atoms (almost all of them hydrogen) from protons and electrons, creating a vast, inflating sea of neutral atoms. Hydrogen is ubiquitous during these times but no stars or galaxies had yet formed, hence giving rise to the nickname Cosmic "Dark Ages." The Dark Ages ended, or began to end, when the first stars formed and began to ionize the hydrogen surrounding the stars. This altered the 21-cm spectrum and 21-cm density fluctuation structure, which the researchers reverse-engineer to infer the properties of those first stars and galaxies. At the 600 million years post-Big-Bang mark, we have the cosmic dawn, the beginnings of the formation of copious stars and galaxies, creating the universe we see when we look up at night, and in fact when we just look around at each other.

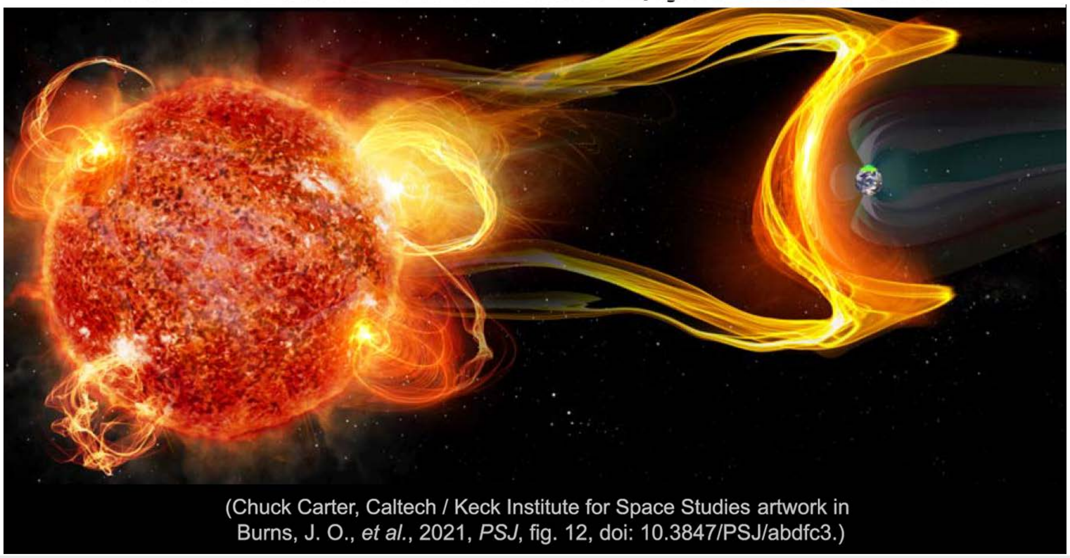


Big events in the history of the universe. The illustration is not to scale and does not convey the expansion of the universe in all directions after the Big Bang. By about 400,000 years after the Big Bang the originally hot universe expanded and cooled enough to precipitate atoms (almost all of them hydrogen) from protons and electrons, creating a vast, inflating sea of neutral atoms. The hydrogen is ubiquitous during these times but no stars or galaxies had yet formed, hence giving rise to the nickname Cosmic "Dark Ages," and necessitating interrogating it with low-frequency radio waves. The Dark Ages ended when the first stars formed accompanied by re-ionization of the atoms.

The universe is teeming with neutral hydrogen atoms. Collisions between hydrogen atoms adds a bit of energy to each atom. This extra energy is radiated away as electromagnetic energy (photons) at a wavelength of 21 cm, corresponding to a radio frequency of 1420 MHz. The Dark Ages may be dark in most wavelengths, but the low-frequency radio waves provide a wealth of information about conditions then and about the changes that led to cosmic dawn, the formation of stars and galaxies, and the re-ionization of atoms. Perhaps most impressive, shifts in the strength of the 1420 MHz signal could lead to new ideas for the physics of dark matter. An interesting twist in observations of the universe far back in time is that when the 21 cm (1420 MHz) signals reach our radio telescopes, they have been redshifted because the universe is expanding. Thus, the actual observations are of radio waves that have frequencies of about 14 MHz. Astronomy is mind boggling!

Other targets are closer to home (in distance and time) studying magnetospheres around the other planets in our Solar System and understanding coronal mass ejections (CMEs) from the Sun, and from other stars to understand the effects on the planets that orbit them.

Artwork of Stellar Coronal Mass Ejections at a Planet

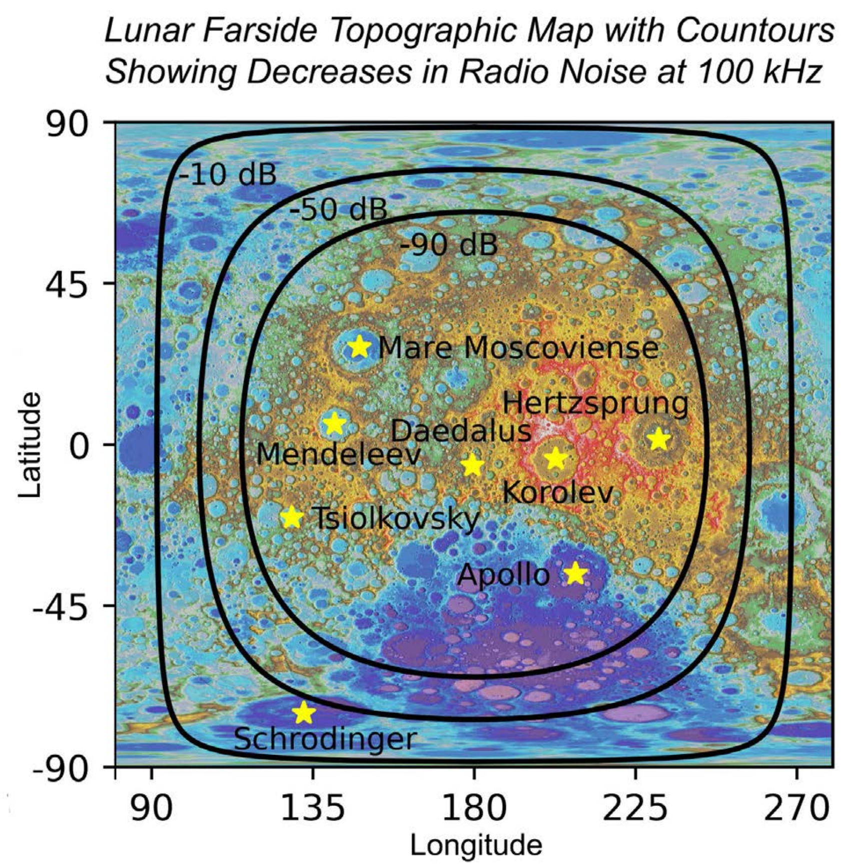


Artist's interpretation of a planet (in this case habitable, shown on the right) being blasted by a coronal mass ejection (CME) from the star it is orbiting. This is an example of processes that can be observed using a lunar radio telescope array. In this example, the observations would shed light on the behavior of other stars and the space weather environment around exoplanets, adding to our understanding of planet habitability.

Going to the Moon to Avoid Terrestrial Radio Noise

To limit light background, astronomers like to install optical telescopes in places far from sources of light such as cities, towns, and highways. Radio astronomers are equally obsessed about polluting their observations with stray human-made radio waves from broadcasting, communications (including cell phones, but especially powerful military and commercial transmitters), and electrical transmission lines. These sources of annoying noise are collectively called radio frequency interference (RFI). Astronomers also deal with natural sources of noise from the atmosphere and ionosphere, such as lightning. These noise sources are particularly loud at low radio frequencies (0.1 to 40 MHz, corresponding to wavelengths of 3000 meters down to 7.5 meters).

The most convenient place to go to solve this noisy problem is the farside of the Moon. The Moon is tidally locked to Earth, so it makes one revolution per orbit around Earth, hence we see only one hemisphere. This is beneficial for radio astronomical observations that need to avoid all that radio frequency interference. The low-frequency radio silence on the lunar farside has been modeled by Neil Bassett (University of Colorado, Boulder) and colleagues at CU Boulder, NASA Ames Research Center, and NASA Goddard Space Flight Center based on spacecraft data (see map below). The base map shows topographic variations on the farside (from 90 to 270 degrees longitude) determined by the Lunar Observer Laser Altimeter (LOLA). White is highest (about 7 km above the mean lunar surface elevation) and the purple is lowest (about 7 km below the mean lunar surface elevation). The large purple splotch is the immense South Pole Aitken impact basin, which is about 2500 km in diameter. The curves show the decreases in radio noise at 100 kHz in Neil Bassett's modeling. The outer curve represents a suppression of only a factor of 10 compared to the nearside (expressed in decibels, a common logarithmic unit for comparing relative frequencies of all sorts of waves, from radio to sound). This is not adequate for making the observations that Jack Burns and his colleagues want to make. The middle curve does the trick, blocking the signal from Earth noise by 50 decibels, a factor of 100,000 compared to the nearside. The innermost curve, which still covers a significant amount of real estate on the farside, drops the noise signal by 90 decibels compared to the nearside, a factor of 1,000,000,000. Decreasing the noise by a factor of a billion will satisfy astronomical needs, no matter how fussy the astronomers and their instruments are.



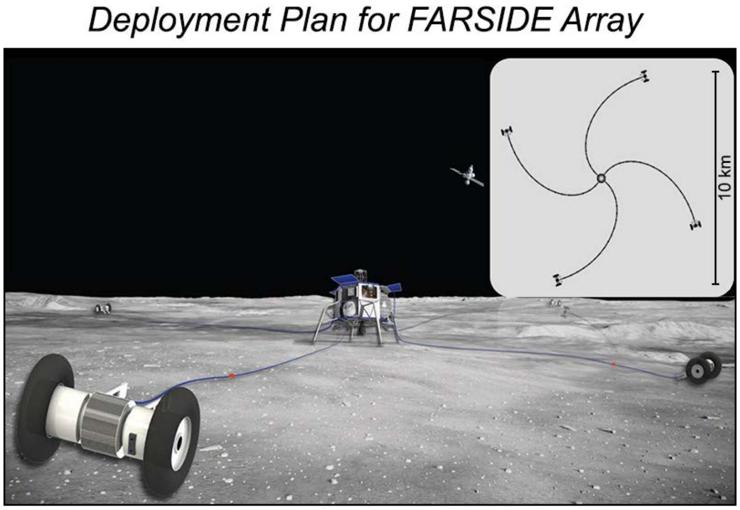
(Burns, J. O., *et al.*, 2021, *PSJ*, fig. 1, doi: 10.3847/PSJ/abdfc3.)

This map shows radio frequency interference (RFI) on the lunar farside compared to levels on the nearside. The lunar farside extends from 90 to 270 degrees longitude. The base map shows lunar topography, with the highest levels colored in white and red, the lowest in purple. Yellow stars are labeled with place names of suitable sites for the FARSIDE observatory because they are smooth. The black curves represent the extent to which interference at low radio frequencies is suppressed compared to the Earth-facing lunar hemisphere, in decibel units: -10 is ten times lower than on Earth-facing side, -50 is a hundred thousand times lower, and -90 is a billion times lower. The radio suppression curves are from Burns et al. (2021) based on modeling by Bassett et al. (2020). Base map is from LROC, Arizona State University and NASA.

Deploying a Low-Frequency Radio Observatory Array on the Moon

There are modest ways to begin low-frequency radio astronomy from the Moon. I will explain that below, but I would like to start with describing Jack Burns' Big Vision (JBBV) of installing an impressive array of radio-wave detectors on the lunar farside. Jack's vision is to convert a 10 km x 10 km region of the dusty lunar farside into a telescopic array that will look back in time to the Dark Ages of the history of the universe. Not back in time to when Jack Burns and I were in elementary school, not back in time when the Moon formed by a giant impact with the still-accreting Earth about 4.5 billion years ago, not back in time when stars and galaxies had only begun to form about 13.2 billion years ago, but to the Dark Ages after the Big Bang, a time about 13.4 (ish) billion years ago. (Units like billions of years do not bother astronomers, planetary scientists, and geologists!)

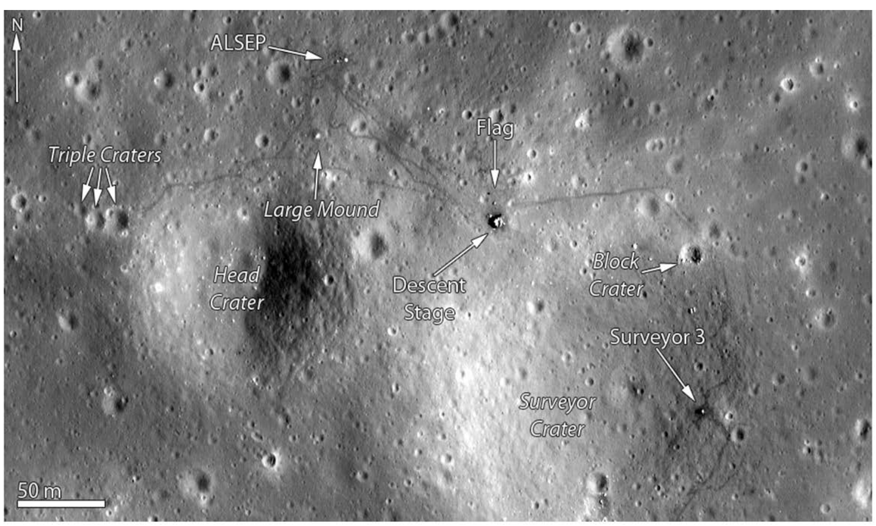
Jack Burns' idea is to use robotic rovers to deploy 128 pairs of antenna nodes on a suitably smooth 10 km x 10 km area on the lunar farside where RFI from Earth does not mask the low-frequency radio signal from the extraordinarily distant past. He and his collaborators call the observatory FARSIDE, an excellent acronym for Farside Array for Radio Science Investigations of the Dark ages and Exoplanets. FARSIDE would be constructed by robotic rovers deploying the 256 dipoles in a spiral pattern within a 10-km square, as illustrated below. The deployment of the array was engineered in collaboration with Blue Origin LLC using the Blue Moon lander in the design.



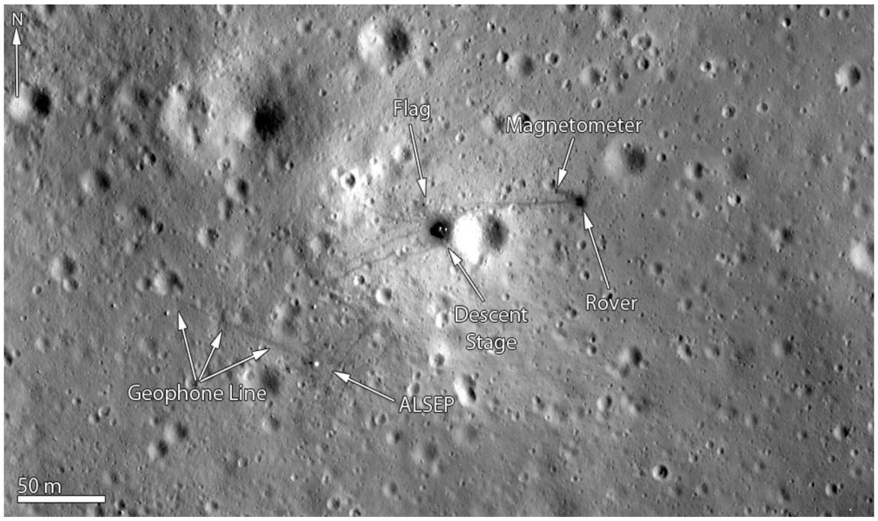
(Burns, J. O., *et al.*, 2021, *PSJ*, fig. 9, doi: 10.3847/PSJ/abdfc3.)

In the current design FARSIDE consists of three major parts, (1) a spacecraft that will transport all the other parts, including the base station that will provide power and communications, (2) four single-axel rovers to deploy antenna nodes, and (3) the antenna array that the rovers will deploy. There will be 128 pairs of antenna nodes. The array will be deployed in a spiral pattern, see the insert at the upper right that shows a view looking down. Tethers connect the base station to the nodes, providing communications and power. The lowest-frequency antennas are incorporated inside the tethers, and a higher frequency set of dipoles are deployed perpendicular to the tether direction. The deployment plan was engineered in collaboration with Blue Origin LLC using the Blue Moon lander in the design. NASA's lunar-orbiting Gateway is shown in the dark sky near the insert (not to scale) and might be used as a data relay to Earth, although there are other possibilities such as a dedicated relay satellite.

Driving four robotic rovers many kilometers on the Moon while deploying tethers and dipole antennas might seem like an impossible challenge on a dusty, cratered surface. But be assured, robotic rover missions to Mars and the Moon (and, of course, the human driven Apollo rovers) have already shown that rovers can readily traverse a barren planetary surface. The requirement for FARSIDE is an observatory site with a 10-meter elevation gradient over an area 10-km in diameter. Experience with the Apollo missions and the high-resolution images taken by the Lunar Reconnaissance Orbiter Camera show that suitable areas are abundant.



Apollo 12 site details, LROC, https://www.lroc.asu.edu/featured_sites/view_site/2



Apollo 16 site details, LROC, https://www.lroc.asu.edu/featured_sites/view_site/5

Images of the undulating terrain at the Apollo 12 [TOP] and Apollo 16 [BOTTOM] landing sites, from orbit and from the surface. The Apollo 12 site is in a maria (the Ocean of Storms), which are typically smooth, though decorated with craters that will need to be avoided during emplacement of the FARSIDE radio array. FARSIDE would target smooth maria or smooth highland plains on the lunar farside (see topographic map above). The Apollo 16 site is in the lunar highlands and has craters, but a farside landing site similar to Apollo 16 would be suitable for constructing the array. Apollo 12 surface photo is NASA image AS12-46-6780. Apollo 16 surface photo is NASA image AS16-114-18423. Click on the images for more information.

Paving the Way with Proof-of-Concept Missions

The full FARSIDE observatory plan is a bit dicey for a risk-averse organization like NASA to jump into without some more modest practice runs. Jack Burns and his collaborators have devised three interesting proof of concept missions, two of which are scheduled to fly on NASA's Commercial Lunar Payload Services (CLPS) initiative. This program is devised for commercial companies of any size to bid on delivering payloads for NASA, including payload integration and operations, launching from Earth and landing on the surface of the Moon. As the **NASA CLPS website** explains, the program was developed "to perform science experiments, test new technologies, and demonstrate capabilities to help NASA explore the Moon and prepare for human missions." Sounds ideal for testing technologies and the extent to which we can really reduce RFI. The two radio astronomy instruments (ROLSES and LuSEE) approved to be included on CLPS missions are briefly described below, along with a third (DAPPER) whose fate is being decided by NASA's Payloads and Research Investigations on the Surface of the Moon (PRISM) program, which will fly science payloads on a CLPS spacecraft. ROLSES and LuSEE are described in Burns et al. (2021).

ROLSES: Radio Wave Observations at the Lunar Surface of the PhotoElectron Sheath
Principal Investigator: Robert MacDowall at NASA Goddard Space Flight Center.
ROLSES radio receiver will be carried by a **NOVA-C spacecraft** from Intuitive Machines and will land on the lunar nearside in Oceanus Procellarum (Ocean of Storms). ROLSES will measure low-frequency radio spectra in the 10 kHz to 30 MHz range. The measurements will help us understand the effects of exposure to the solar wind and ultraviolet light, which charge the dusty lunar surface, levitating the dust and transporting it around the Moon. This will improve our understanding of the photoelectron plasma sheath 1 to 3 meters above the surface and how the plasma interactions aid in dust transport, which has important implications for human exploration of the Moon. It will also provide vital information on how well a nearside radio observatory could monitor radio bursts from the Sun.

LuSEE: Lunar Surface Electromagnetic Experment
Principal Investigator: Stuart Bale at the University of California at Berkeley.
LuSEE will measure radio signals in the 10-45 MHz range, which includes signals from the Sun, Earth, and outer planets. It will land in the Schrödinger Basin on the lunar farside (it is labeled on the farside map shown above). A central goal is to measure the RFI on a place on the lunar farside to test the veracity of the data-based modelling done to characterize the RFI on the farside. The prediction is that there will be measurement noise, so that it can be characterized to help plan other missions. The instrument will, like ROLSES, provide information about the surface plasma sheath, its role in dust transport, and its interactions with the Earth's magnetotail. Perhaps most important, LuSEE will test our ability to detect distant signals from the young

universe, while measuring radio bursts from other planets in our Solar System.

DAPPER: Dark Ages Polarimeter PathfindER
Principal Investigator: Jack Burns at the University of Colorado, Boulder.
DAPPER is a proposed instrument to fly with LuSEE to the Schrödinger Basin. It would measure radio signals in the 40-110 MHz range and would be the first direct pathfinder mission for FARSIDE. It would test our ability to peer into the deep distant past to understand the Dark Ages. Team Burns have proposed that the mission could fly to Schrödinger Basin with LuSEE, thereby providing the appropriate range of frequencies to examine the 21-cm radio signals from the Dark Ages (red shifted, of course) in the combined 10 to 110 MHz range. It would be humanity's first crack at doing cosmology from the Moon, paving the way for clearer views provided by ambitious, imaginative projects like FARSIDE.

Science from the Moon

The astronomical observatories described here and elsewhere, the extensive geological studies aimed at understanding the origin and evolution of the Moon, the visits to hundreds of craters to determine how the flux of impactors varies with time, the search for and extraction of resources to use on the Moon and throughout the inner Solar System, and the entire process of us figuring out how to live on another planetary body with no atmosphere, require an extensive human and robotic infrastructure on the Moon. Human settlement and its infrastructure open vast vistas for science and applied science activities on the Moon. The exciting possibilities from low-frequency radio arrays on the farside are only the beginning of using the Moon to satisfy human curiosity about our origins.

Additional Resources

Links open in a new window.

- **PSRDpresents:** Seeing What We Have Never Seen Before: Low-Frequency Radio Astronomy from the Moon -- **Slide Summary** (with accompanying notes).

- Bassett, N., Rapetti, D., Burns, J. O., Tauscher, K., MacDowall, R. (2020) Characterizing the radio quiet region behind the lunar farside for low-radio frequency experiments, *Advances in Space Research,* v. 66, 1265-1275, doi: 10.1016/j.asr.2020.05.050. [**article**]
- Burns, J. O. et al. 2019, Probe study report: FARSIDE (Farside Array for Radio Science Investigations of the Dark ages and Exoplanets), NASA. [**report pdf**]
- Burns, J. O. (2020) Transformative science from the lunar farside: Observations of the dark ages and exoplanetary systems at low radio frequencies, *Philosophical Transactions of the Royal Society A,*, 379:20190564, doi: 10.1098/rsta.2019.0564. [**article**]
- Burns, J. O., MacDowall, R., Bale, S., Hallinan, G., Bassett, N., and Hegedus, A. (2021) Low radio frequency observations from the Moon enabled by NASA landed payload missions, *The Planetary Science Journal,* 2:44, doi: 10.3847/PSJ/abdfc3. [**open access article**]