

Radio Astronomy from the Moon:

A discussion on the science from upcoming NASA Commercial Lunar Payload Services (CLPS) missions to the lunar surface with low frequency (<100 kHz) radio astronomy instruments

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Outline

- Bio
- Planetary Science Research
- CLPS Program
- Intro to Radio Astronomy
- Radio Science Payloads: ROLSES, LuSEE
- My CLPS Deliveries: NMLS, CP11
- Future Lunar Missions: FARSIDE
- Q&A

Image Source:
Clementine, NASA

Education Path



- Bachelors of Science, Physical Science, Biola University , La Mirada, California
- Bachelors of Science, Aerospace (Astronautics) Engineering, Univ. Southern California (USC)
- Masters of Science, International Space University, Strasbourg, France
- PhD, Earth & Planetary Science, University of California, Berkeley
 - Geophysics
 - Dissertation: Identifying induced magnetic fields of the Moon

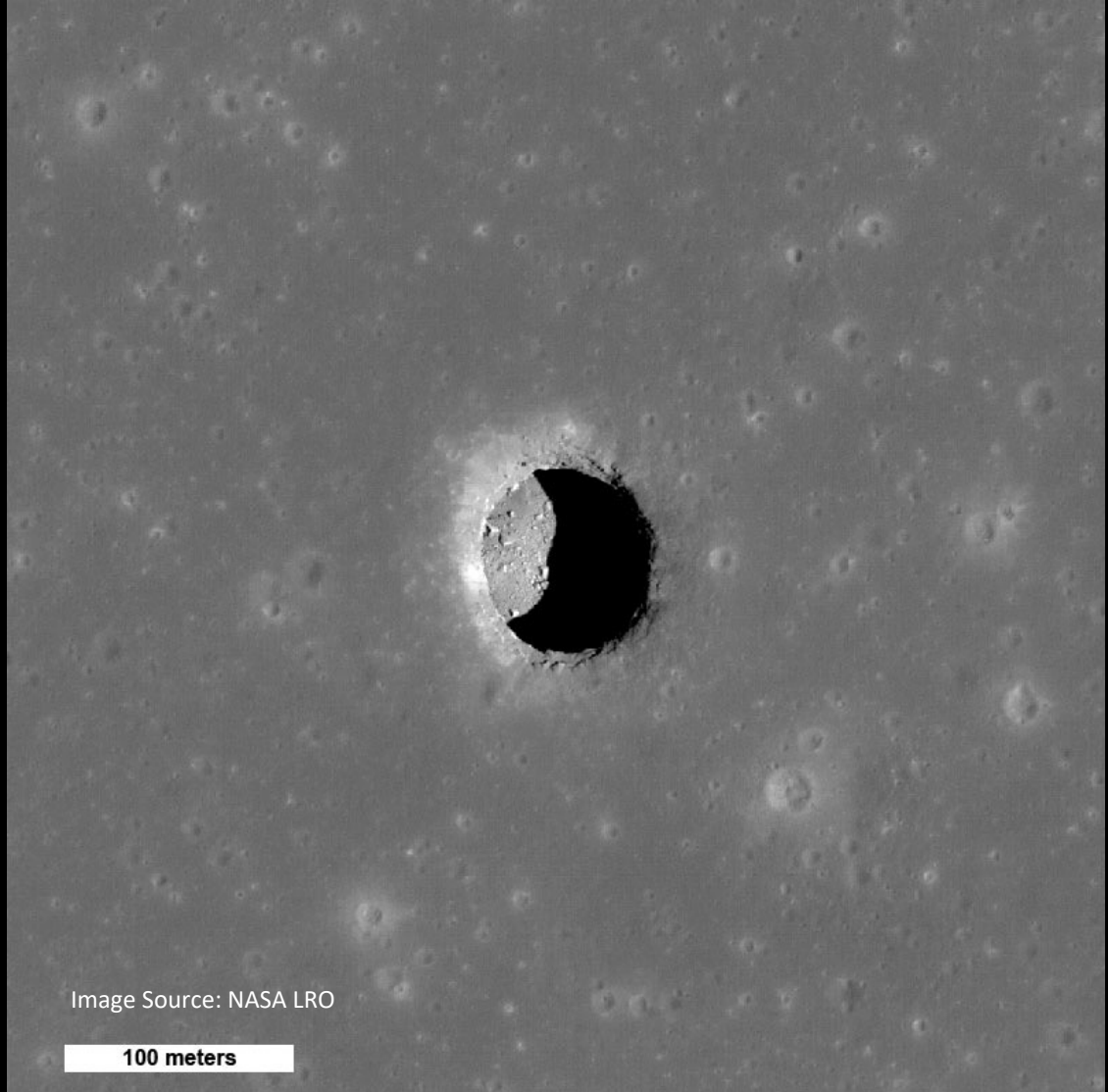


Career Path

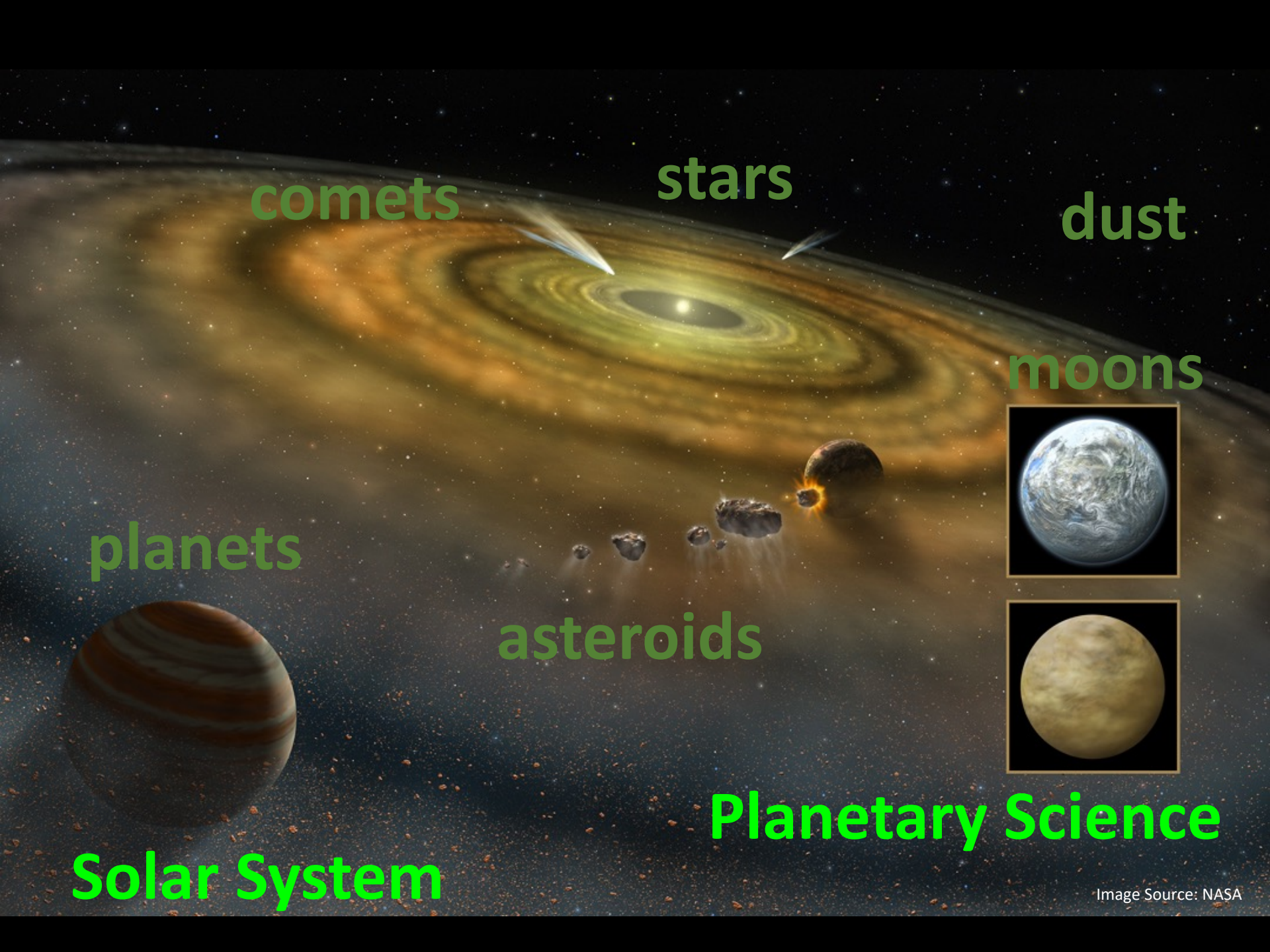
- Engineering Internships, Boeing, Northrop Grumman & NASA Ames
- Mechanical Integration & Test Engineer, Northrop Grumman
- Mechanical Design Integration, Systems Engineering, Northrop Grumman
- Graduate Student Instructor & Researcher, UC Berkeley, Space Sciences Lab
- Invited Guest Researcher, Louisiana State University, Geology & Geophysics Department
- Research Scientist, NASA MSFC



What is a planet? How do we learn about planets?







comets

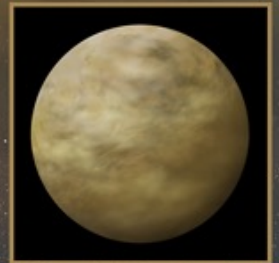
stars

dust

moons



planets



asteroids

Planetary Science

Solar System

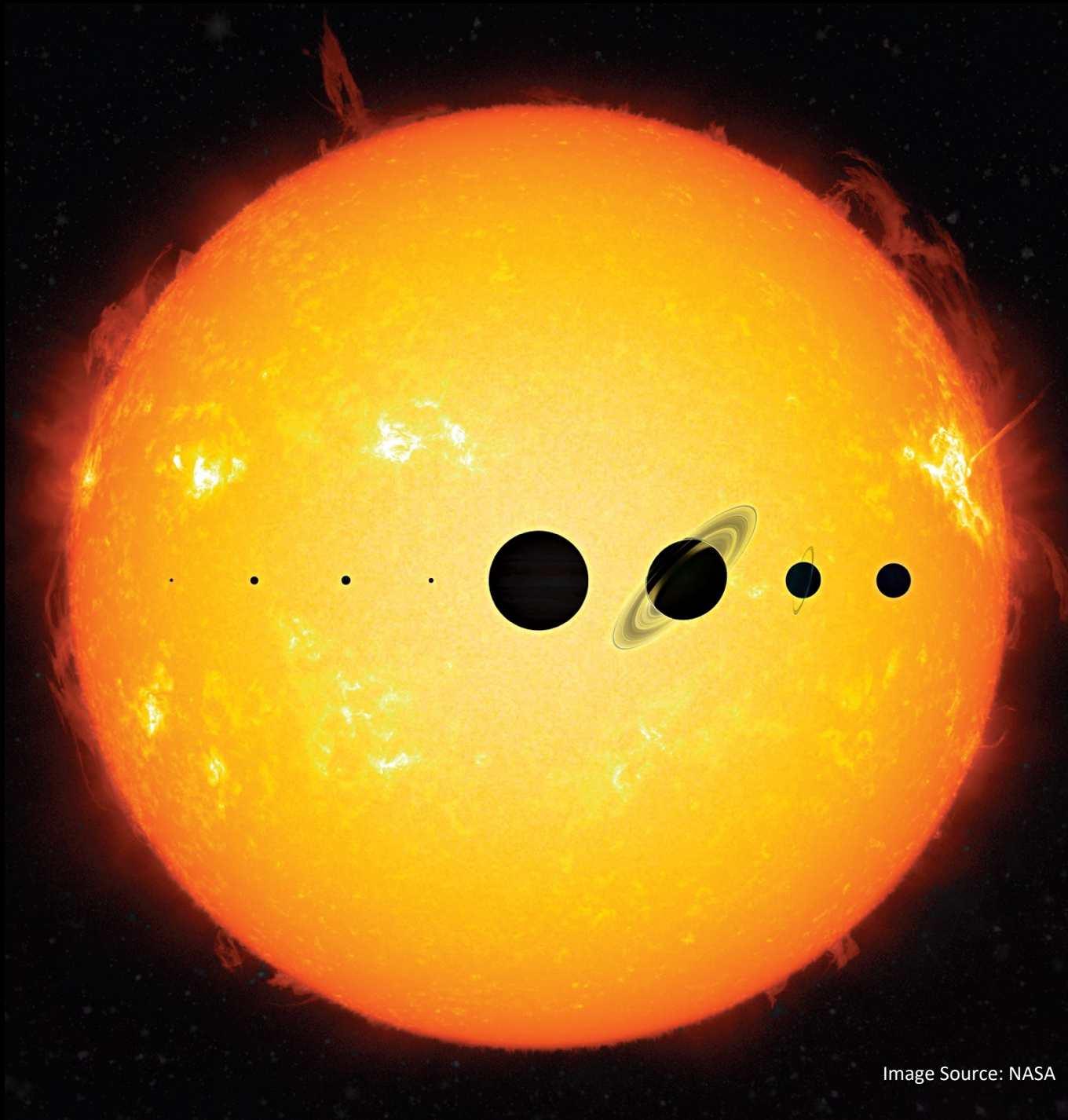


Image Source: NASA

Artemis Phase 1: To the Lunar Surface by 2024

2025?

Artemis 1: First human spacecraft to the Moon in the 21st century

Artemis 2: First humans to the Moon in the 21st century

First high power Solar Electric Propulsion (SEP) system

First Pressurized Crew Module delivered to Gateway

Artemis 3: Crewed mission to Gateway and lunar surface

Commercial Lunar Payload Services

- CLPS delivered science and technology payloads

Early South Pole Crater Rim Mission(s)

- First robotic landing on eventual human lunar return and ISRU site
- First ground truth of polar crater volatiles

Large-Scale Cargo Lander

- Increased capabilities for science and technology payloads

Humans on the Moon - 21st Century

First crew leverages infrastructure left behind by previous missions

LUNAR SOUTH POLE TARGET SITE

2022

2025

Commercial Lunar Payload Services (CLPS) Vendors

- The Government awarded 9 fixed-price, indefinite delivery indefinite quantity contracts in November 2018 and added 5 more companies in November 2019.
- Expected Task Order cadence of 2 per year.
- ★ Active Task orders



Commerical Lunar Payload Services (CLPS)

CS-3 Orbital Flight

CP-21 Gruithuisen Domes

**CP-11 Reiner Gamma
*Intuitive Machines***

2022

2023

2024

2025

TO = Task Order

CS = CLPS Science (NASA STMD)

CP = CLPS PRISM (NASA SMD)

**TO2-AB, Lacus Mortis
*Astrobotic***

**TO2-IM, Mare Crisium
*Intuitive Machines***

**TO-19D, Mare Crisium
*Firefly Aerospace***

**South Pole:
PRIME-1, Shackleton
Connecting Ridge
*Intuitive Machines***

**TO-19C, Rim of Haworth crater
*Masten Aerospace***

**VIPER (TO-20A), Nobile
*Astrobotic***

CP-22 South Pole

**CP-12 Schrödinger
Basin, *Draper***

8.4.2022

2022-2023

TO2 AB – Lacus Mortis Q4 2022

2023

PRIME-1 – South Pole (CY Q2)

TO2 IM Mare Crisium (CY Q1)

TO 19 C Haworth Crater (South Pole)

2024

TO 19D Mare Crisium

TO 20A Nobile (South Pole)

TO CP-11 Reiner Gamma (Q2)

2025

TO CP-12 Schrodinger Basin

TO CP-21 Gruithuisen Domes (Announced)

CP-22 South Pole (Announced)

CS-3 Orbital flight

CLPS Active Task Order Portfolio

*TO2 AB; Q4 2022
Astrobotic
Peregrine*



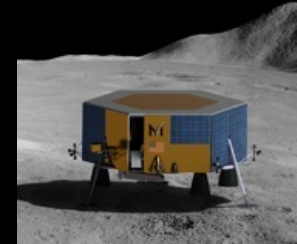
*TO2 IM; Q1 2023
Intuitive Machines
NOVA-C*



*TO PRIME-1; Q2 2023
Intuitive Machines
NOVA-C*



*TO19C Q4 2023
Masten
XL-1*



*TO 19D; 2024
Firefly Aerospace
Blue Ghost*



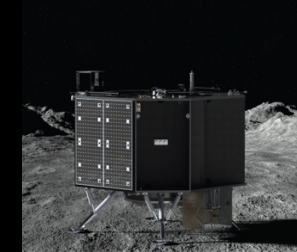
*TO 20A VIPER; 2024
Astrobotic
Griffin*



*TO CP11; 2024
Intuitive Machines
NOVA-C*

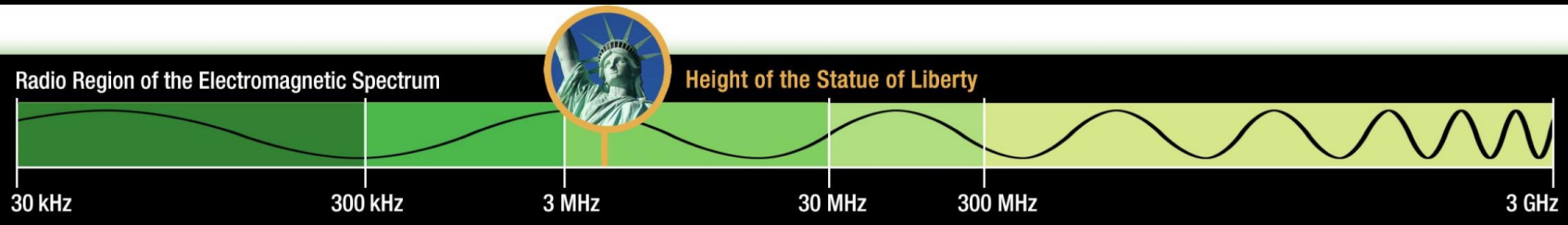


*TO CP12; 2025
Draper*

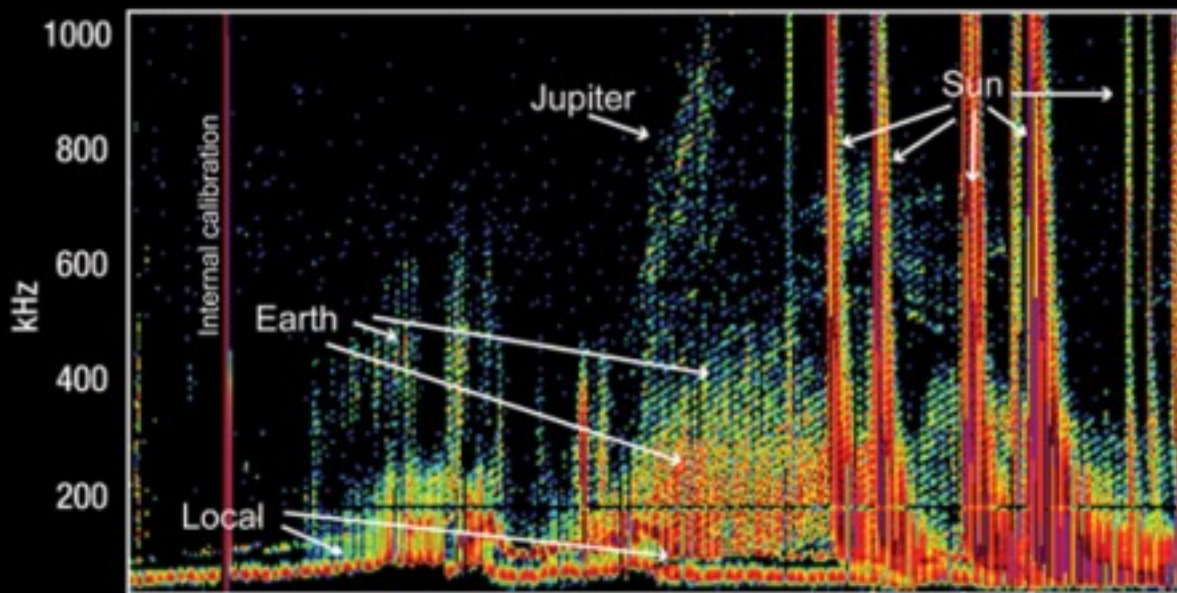


Viper Video:
<https://youtu.be/pvf1Csn1wRU>

Radio Waves



RADIO EMISSIONS



One day of Radio Emissions

3pm Big Spring D
Forum:
Meteor Scatter
Communications:
The Science
Behind the Pings
Rob Suggs, PhD,
NN4NT

Radio Telescopes



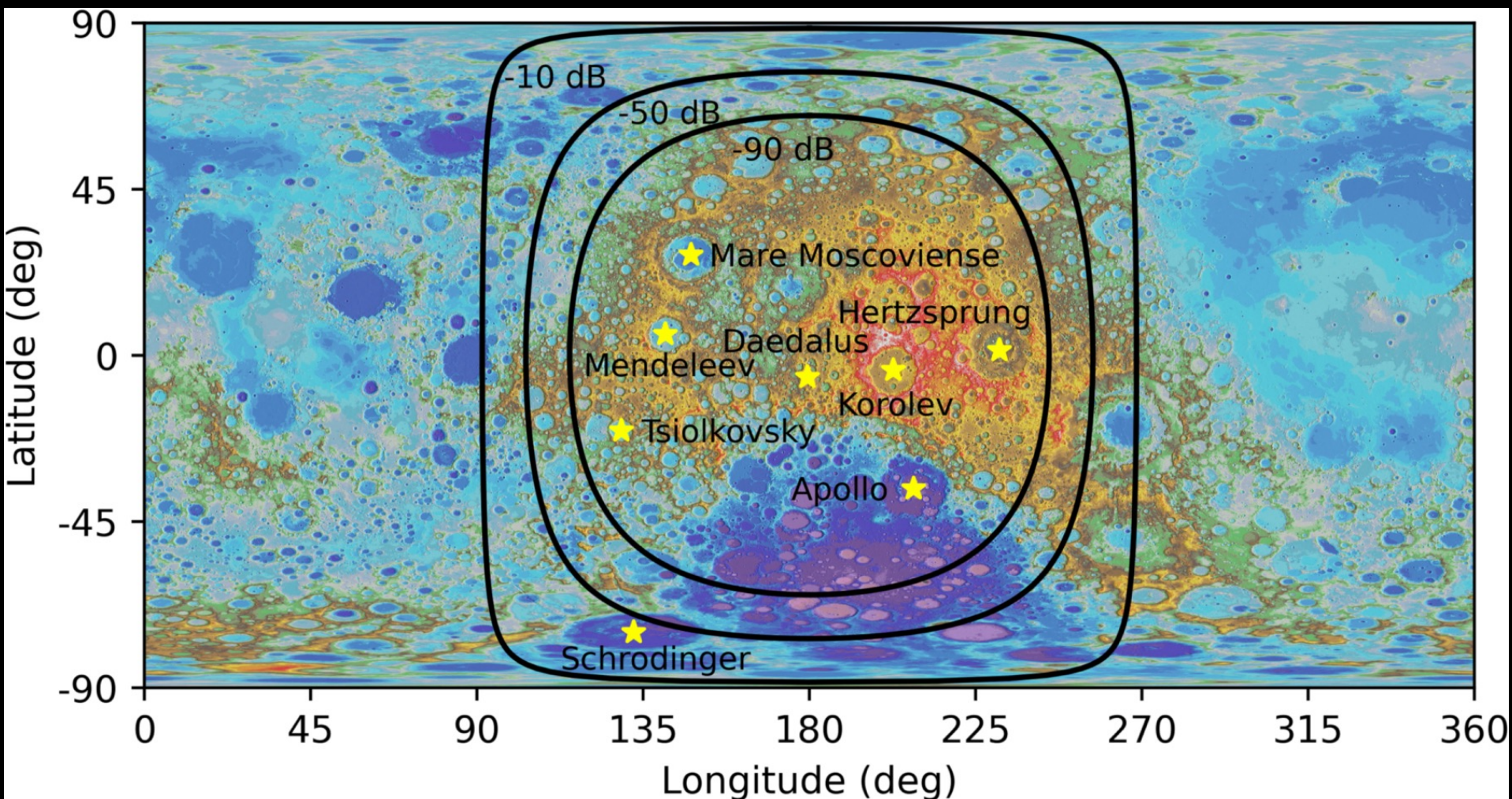
Lunar Farside Radio astronomy



Radio telescopes on the farside of the Moon improve observations at $\sim$ kilometer wavelengths (~ 0.3 MHz) over interference from ionospheric and human-produced radio frequency interference.

Burns *et al* 2021 *Planet. Sci. J.* **2** 44, <https://doi.org/10.3847/PSJ/abdfc3>

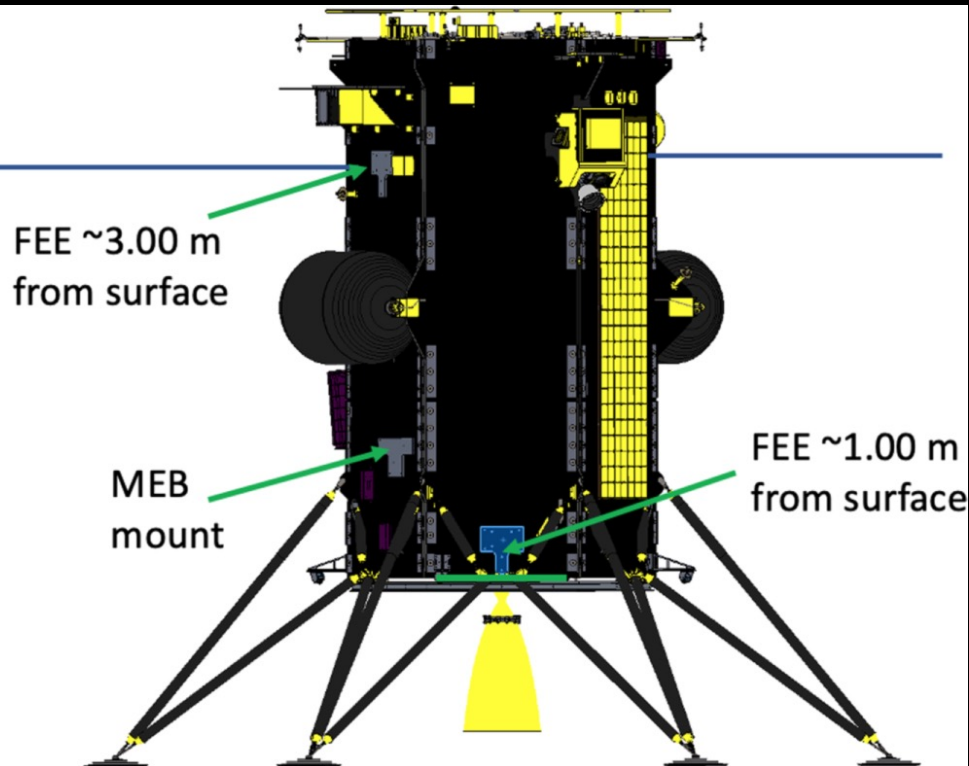
Radio Frequency Suppression



Map of RFI suppression at 100 kHz based upon numerical simulations from Bassett et al. (2020). Contours indicate suppression of -10 , -50 , and -90 dB relative to the incident intensity. Map colors indicate elevation. Potential landing sites are indicated by the yellow stars.

Burns et al 2021 *Planet. Sci. J.* 2 44, <https://doi.org/10.3847/PSJ/abdfc3>

ROLSES: Radio wave Observations at the Lunar Surface of the photoelectron Sheath



Radio spectra from 10 kHz–30 MHz, will investigate the plasma environment above the lunar surface and measure the fidelity of radio spectra on the surface. Locations of Electronics are noted. Proof of concept that good, clean radio measurements can be made on the Moon.

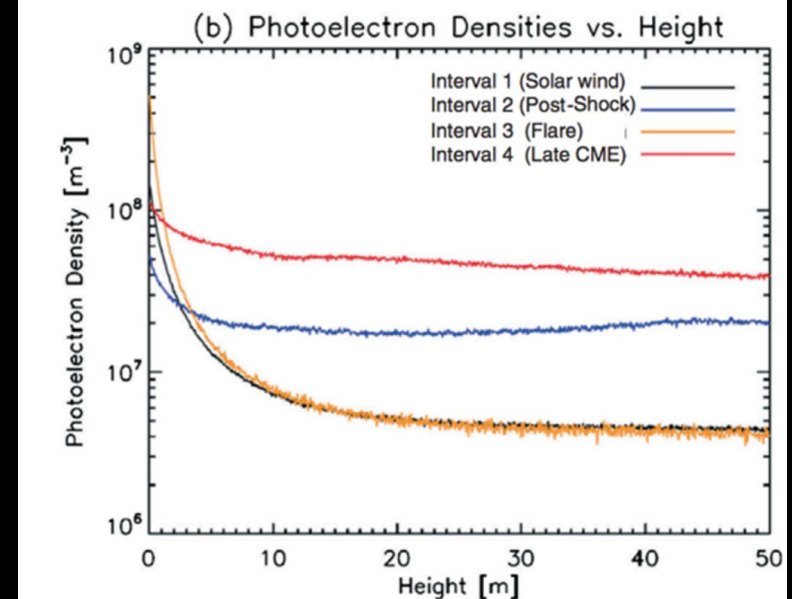
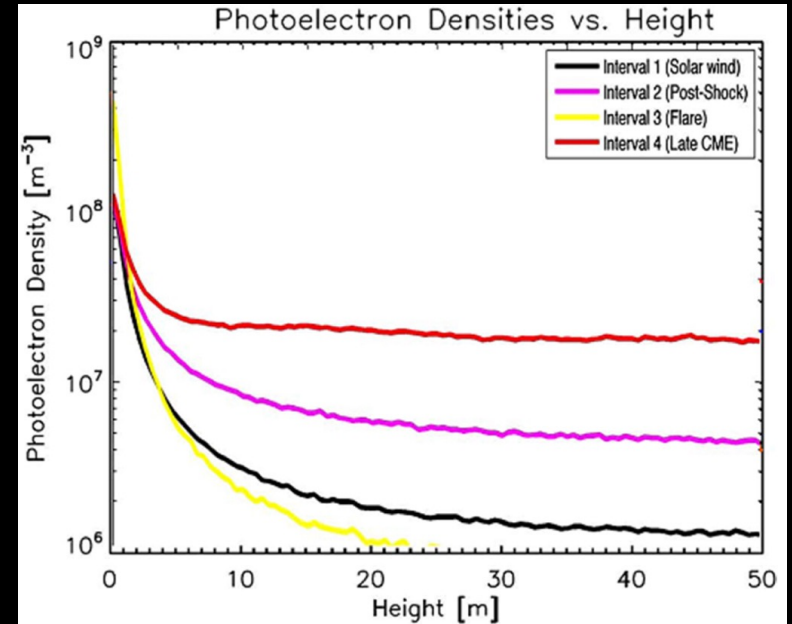




Image Credit: NASA, Jim Spann

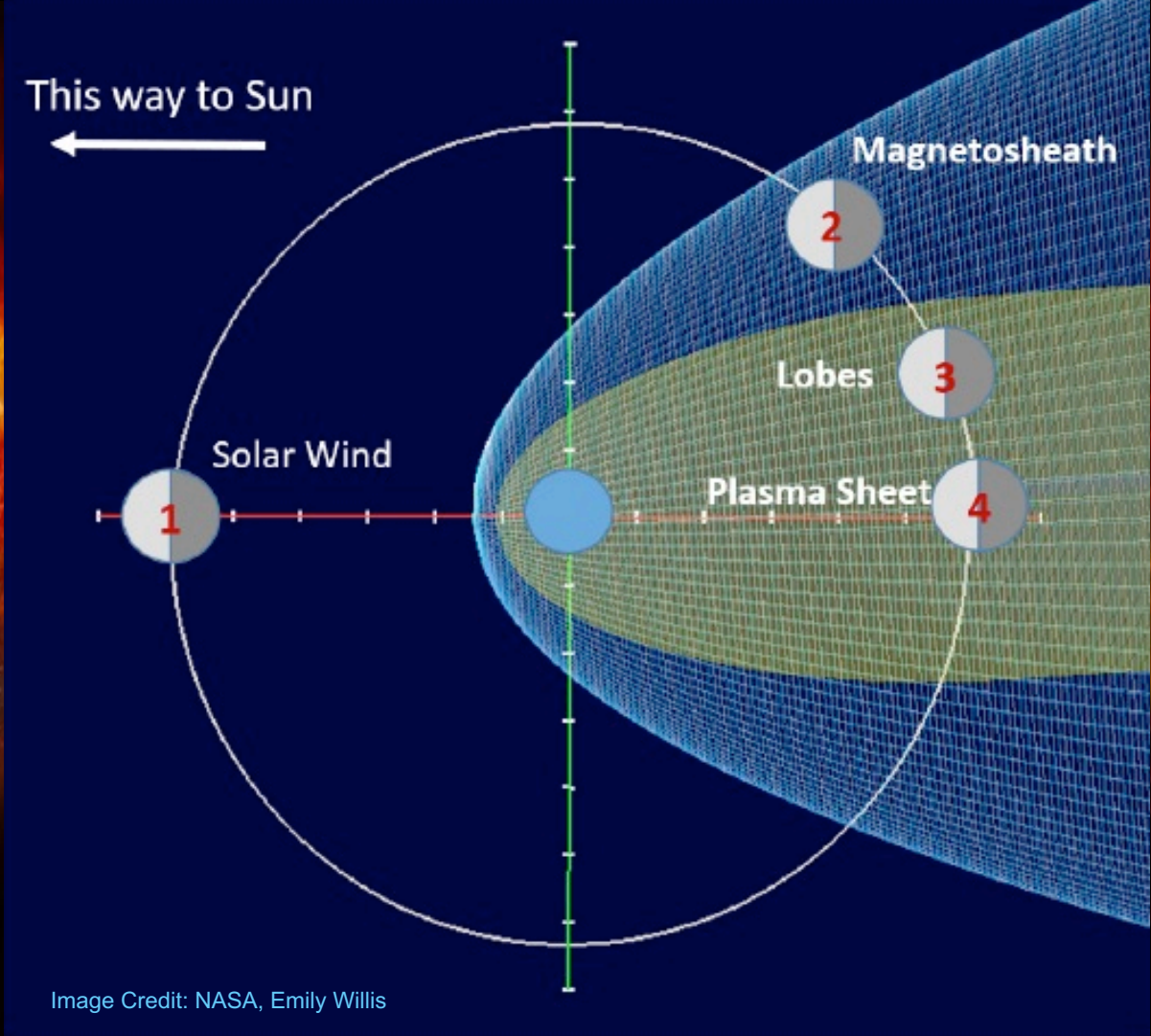


Image Credit: NASA, Emily Willis

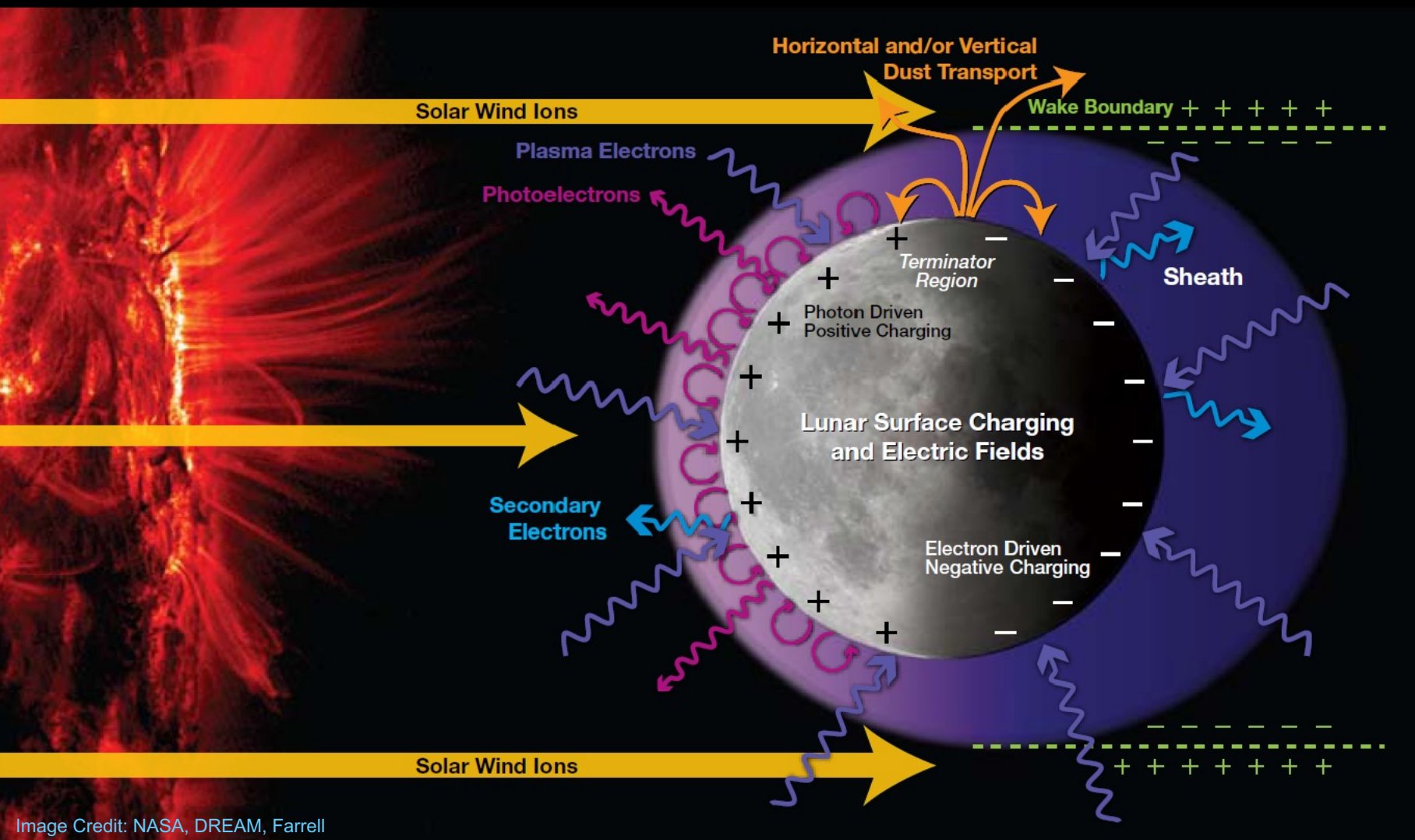
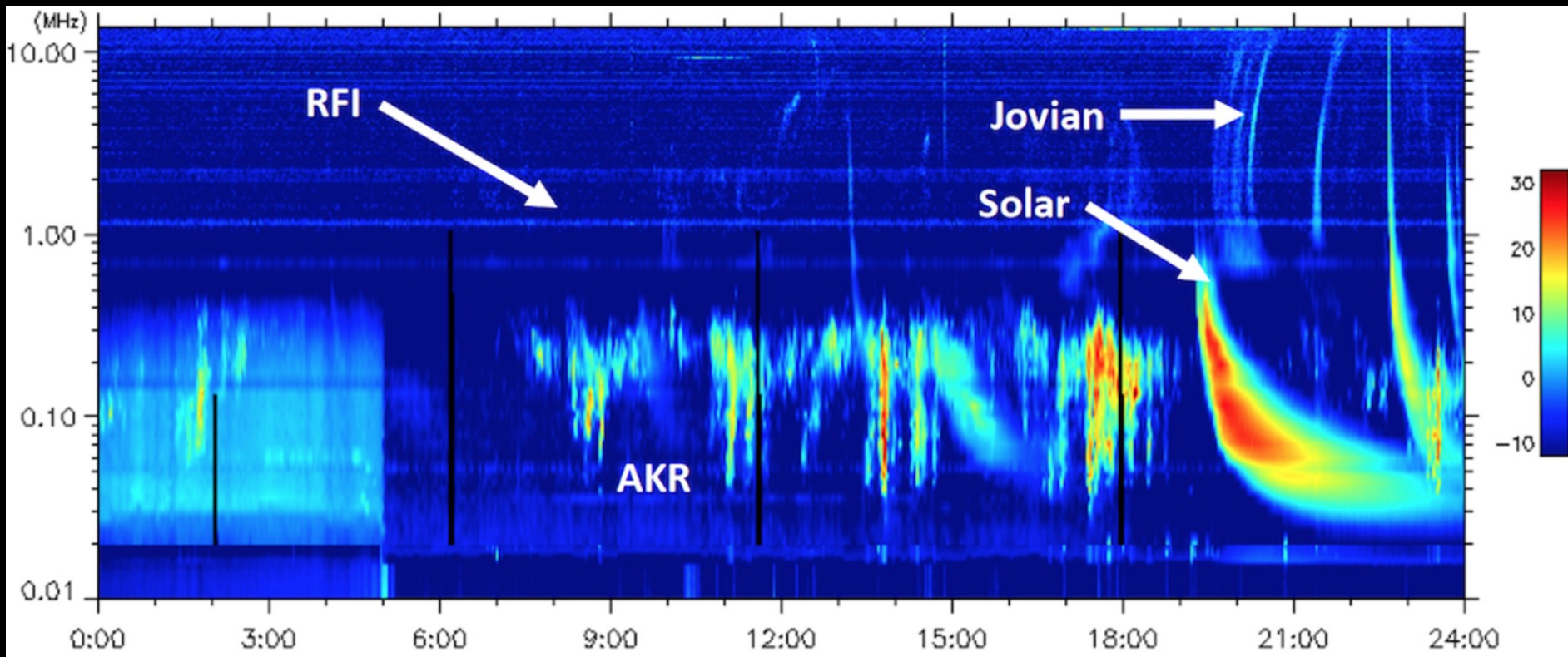


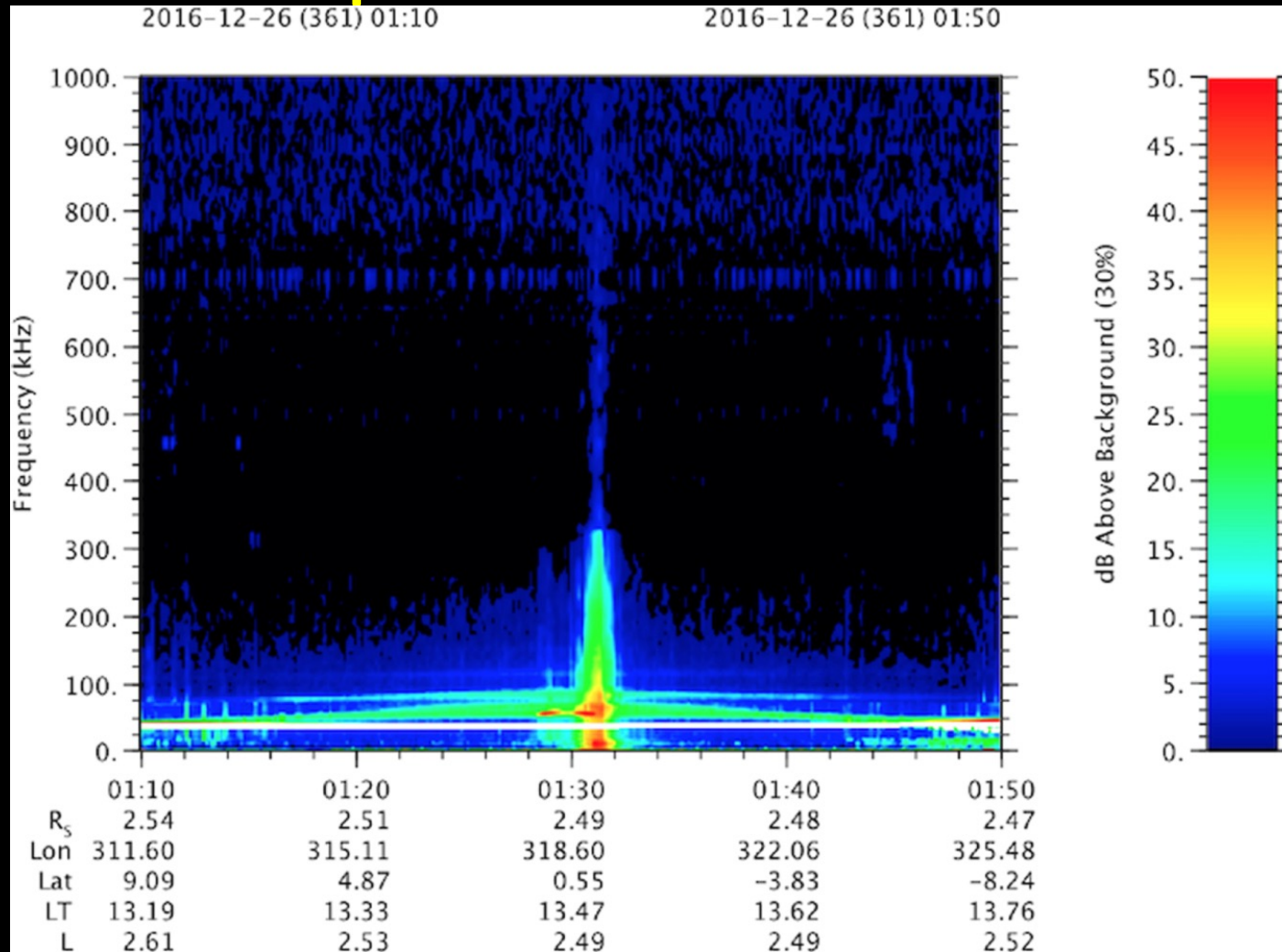
Image Credit: NASA, DREAM, Farrell

ROLSES Expected Observations



The WAVES instrument on the Wind spacecraft (Bougeret et al. [1995](#)) at Sun–Earth L1 shows solar radio bursts, Earth's auroral kilometric-wavelength radio bursts (AKR), terrestrial ground-based transmitters (RFI), and Jovian radio emissions, during a 24 hr interval on 2012 February 20. ROLSES will be capable of making similar observations, which would demonstrate some of the science data provided by the lunar radio array, FARSIDE

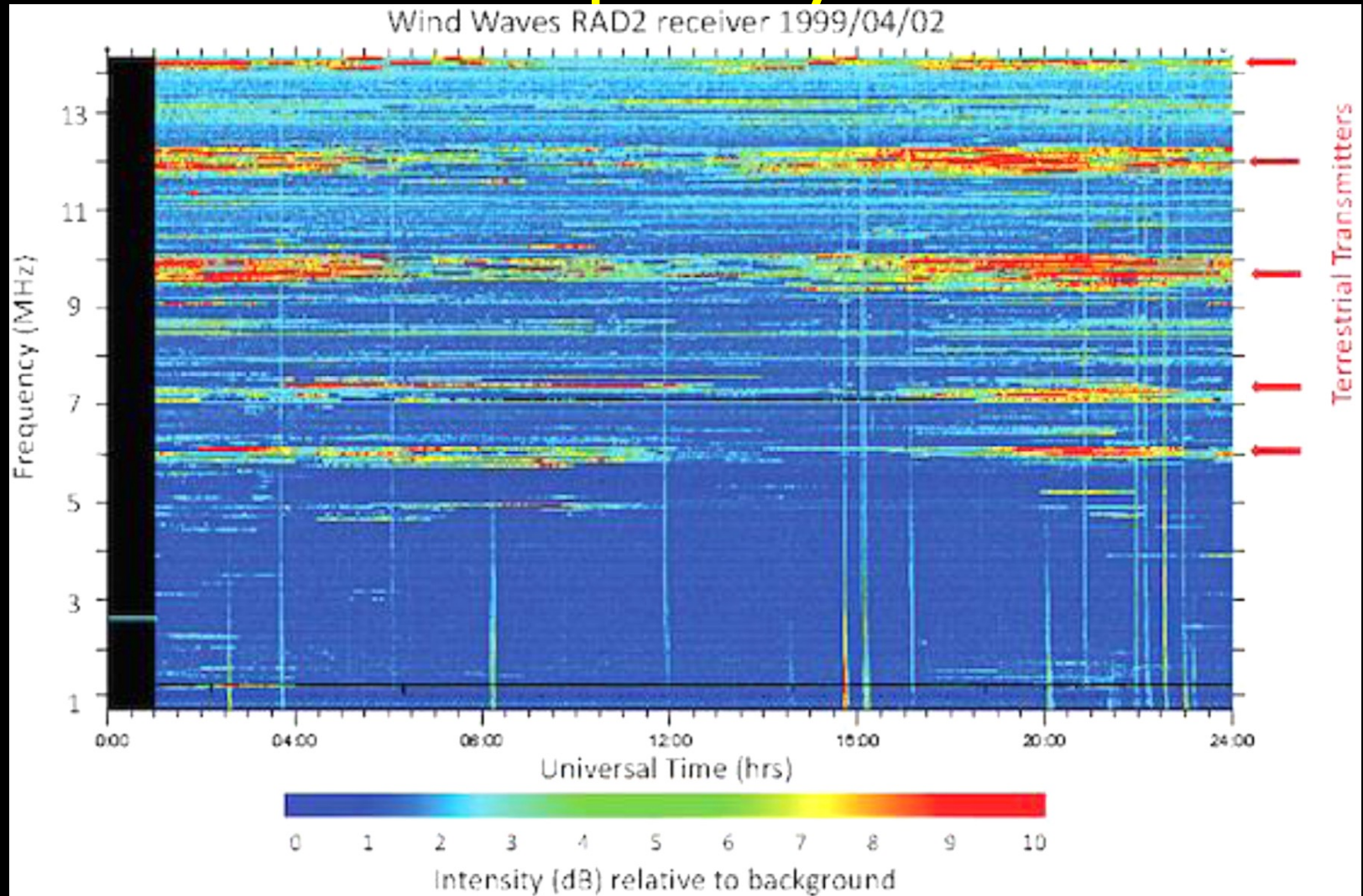
ROLSES Expected Observations



Plot showing the dust signal detected by the Cassini spacecraft when crossing the Saturn F-ring.

Burns *et al* 2021 *Planet. Sci. J.* **2** 44, <https://doi.org/10.3847/PSJ/abdfc3>

Earth Radio Frequency Interference



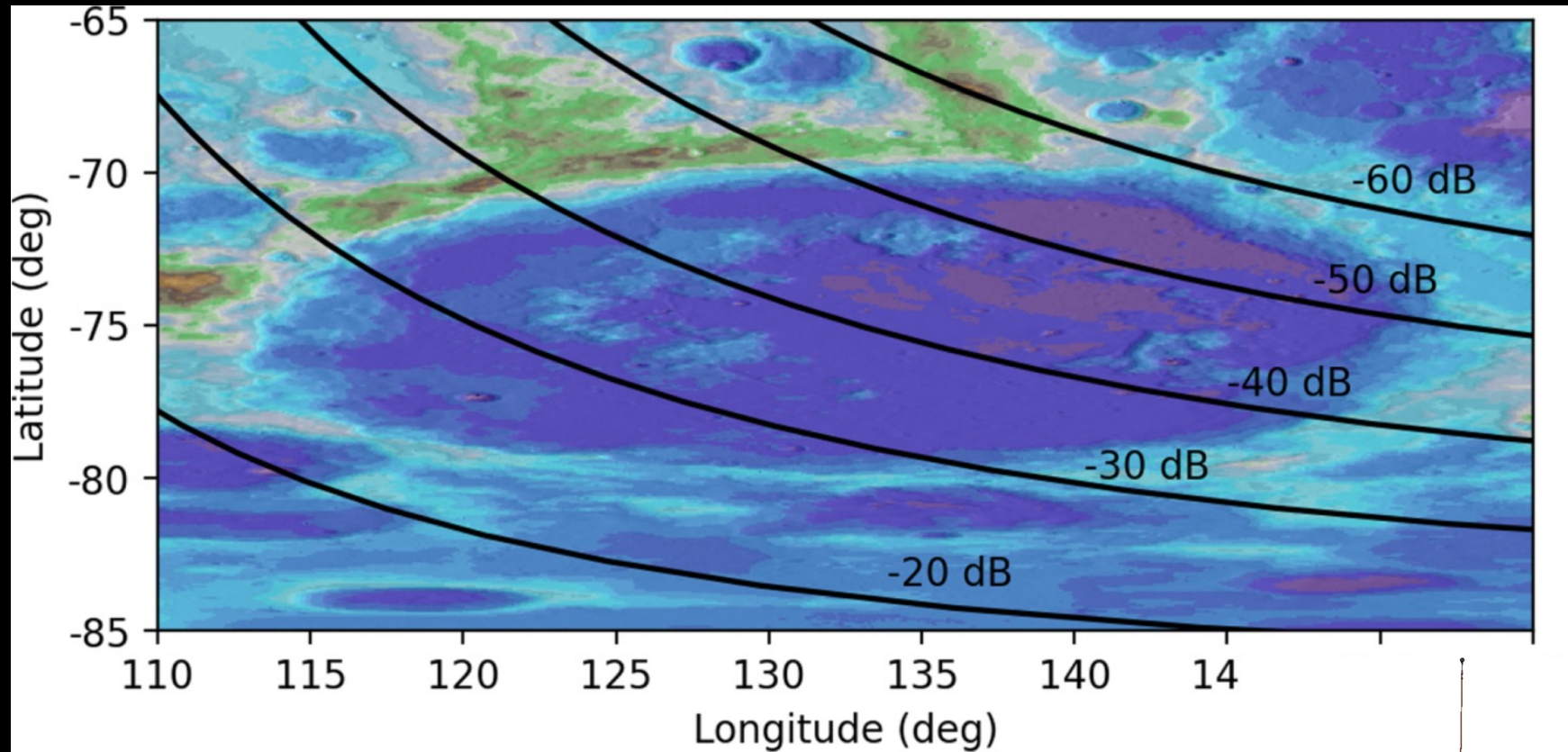
Dynamic spectrum shows terrestrial RFI observed by Wind/WAVES on 1999 April 2 when it passed the Moon

Burns *et al* 2021 *Planet. Sci. J.* **2** 44, <https://doi.org/10.3847/PSJ/abdfc3>

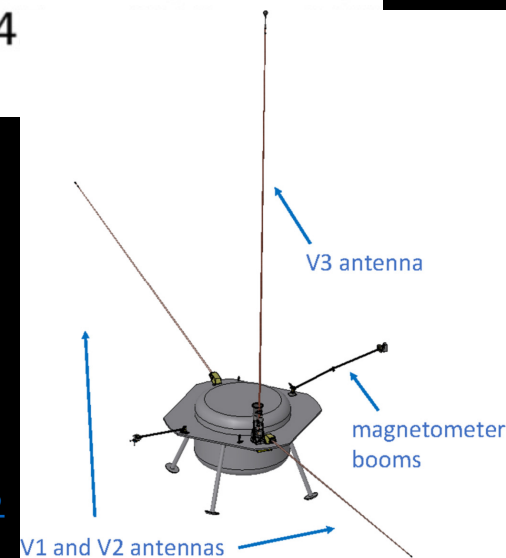
ROLSES

- ROLSES will measure the photoelectron sheath density to better understand the charging of the lunar surface via photoionization and impacts from the solar wind, charged dust, and current anthropogenic radio frequency interference.

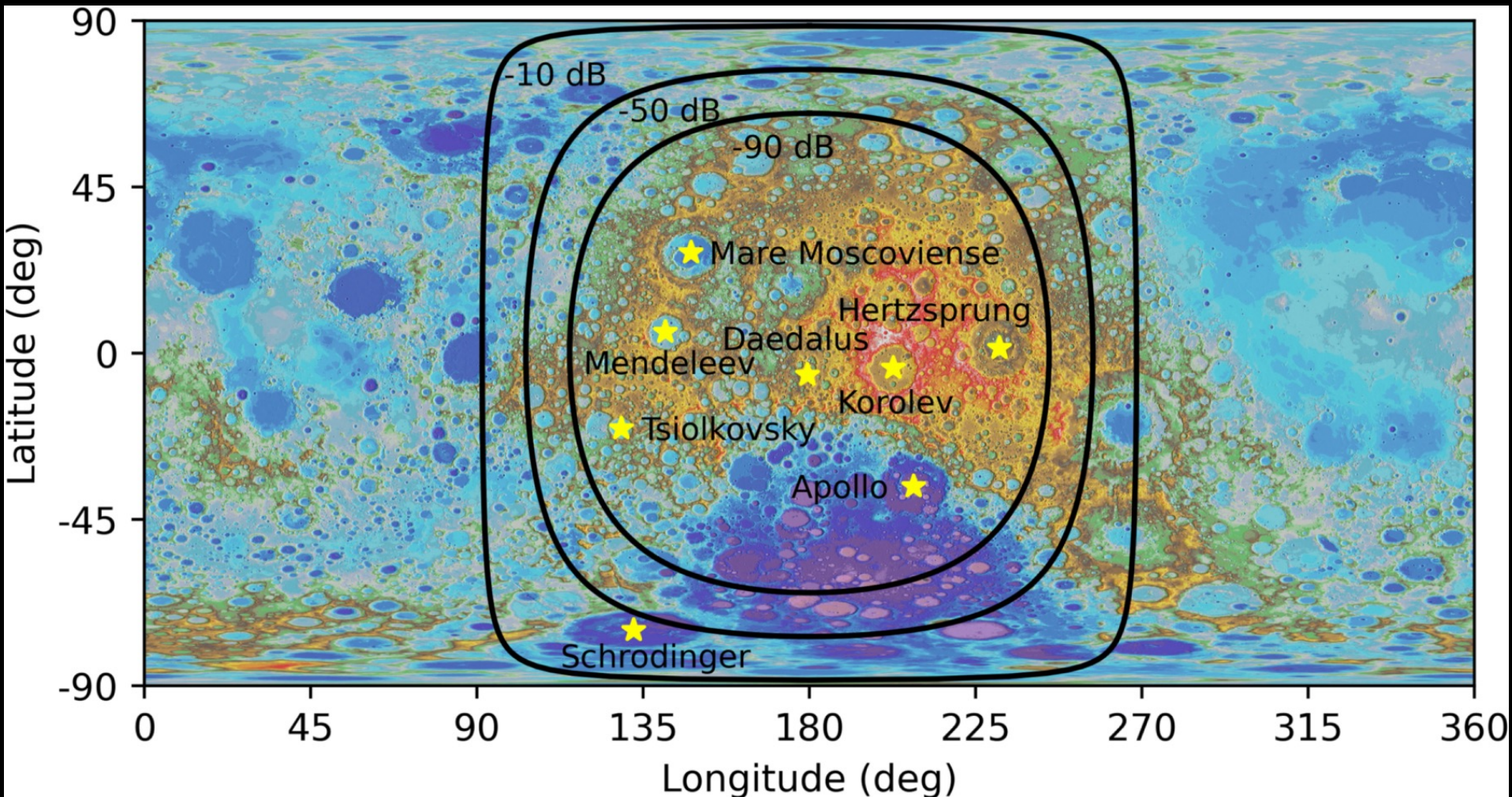
LuSEE: Lunar Surface Electromagnetics Experiment



At 100 kHz, the level of suppression of radio interference will vary significantly across the basin. As shown in Figure 7, the level of attenuation varies from a factor of approximately 25 dB at the southwest corner of the basin to near 55 dB at the northeast corner



Radio Frequency Suppression



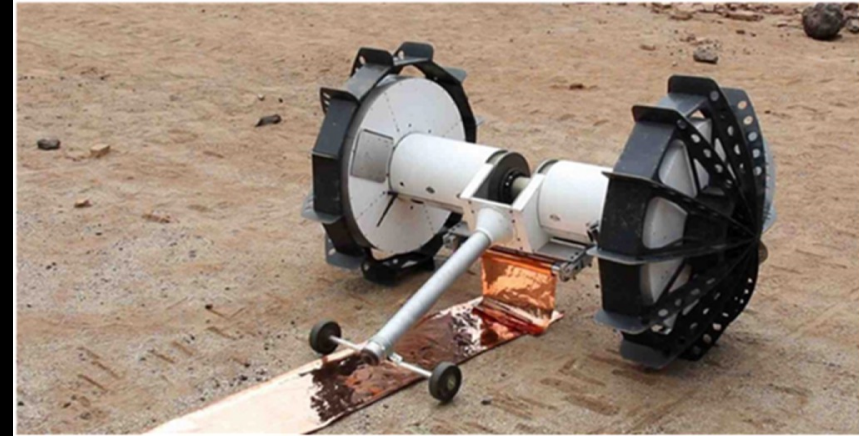
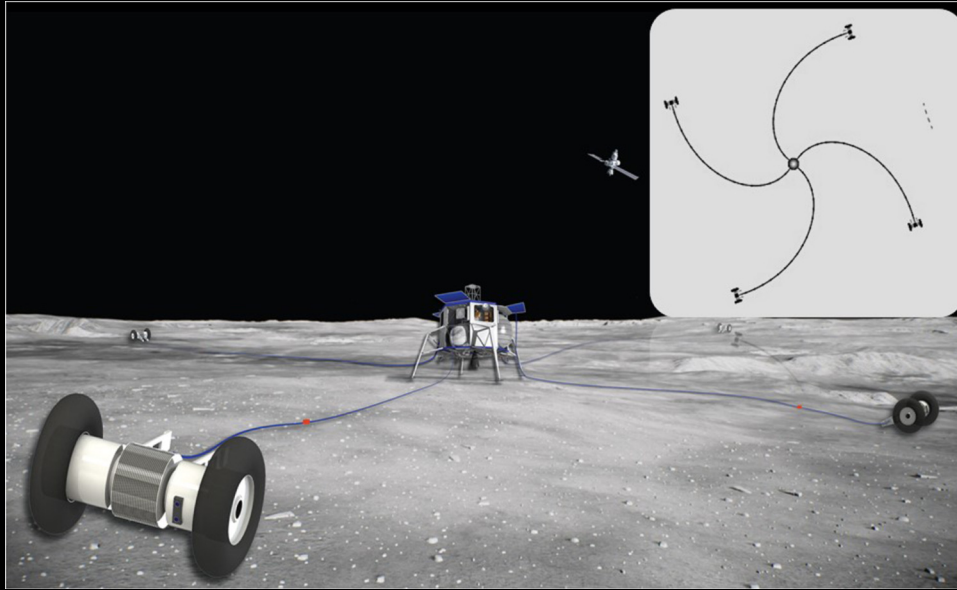
Map of RFI suppression at 100 kHz based upon numerical simulations from Bassett et al. (2020). Contours indicate suppression of -10 , -50 , and -90 dB relative to the incident intensity. Map colors indicate elevation. Potential landing sites are indicated by the yellow stars.

Burns et al 2021 *Planet. Sci. J.* 2 44, <https://doi.org/10.3847/PSJ/abdfc3>

LuSEE

- LuSEE will measure the local magnetic field and exo-ionospheric density, interplanetary radio bursts, Jovian and terrestrial natural radio emission, and the galactic synchrotron spectrum.
- LuSEE is a suite of sensors and electronics designed to make comprehensive measurements of the electromagnetic environment of the lunar surface from DC to radio frequencies (~ 20 MHz).

Farside Array for Radio Science Investigations of the Dark ages and Exoplanets (FARSIDE) Future Mission Concept

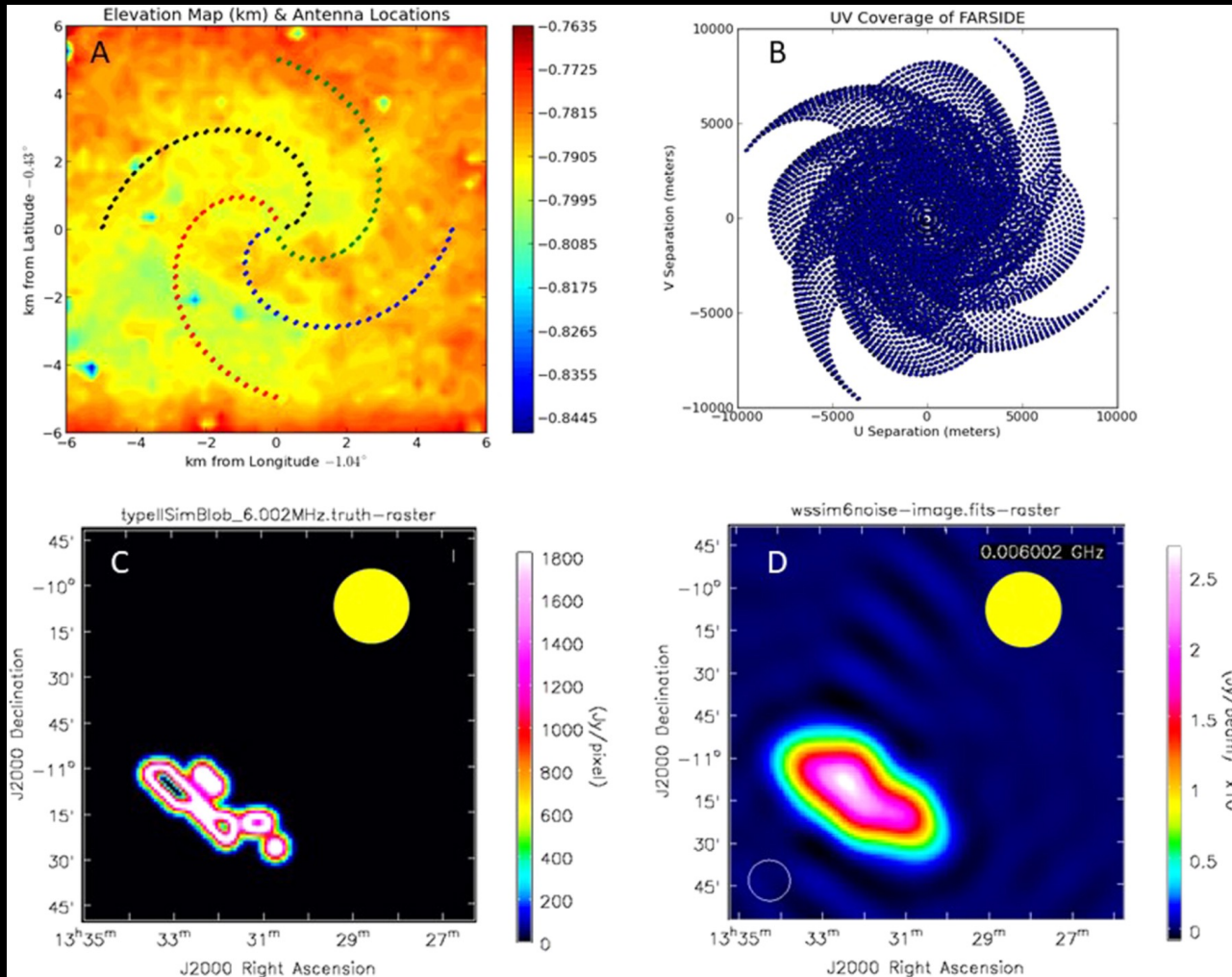


- 10 km diameter interferometric array
- 128 pairs of dipole antennas
- the first radio interferometers on the Moon

FARSIDE would break new ground by:

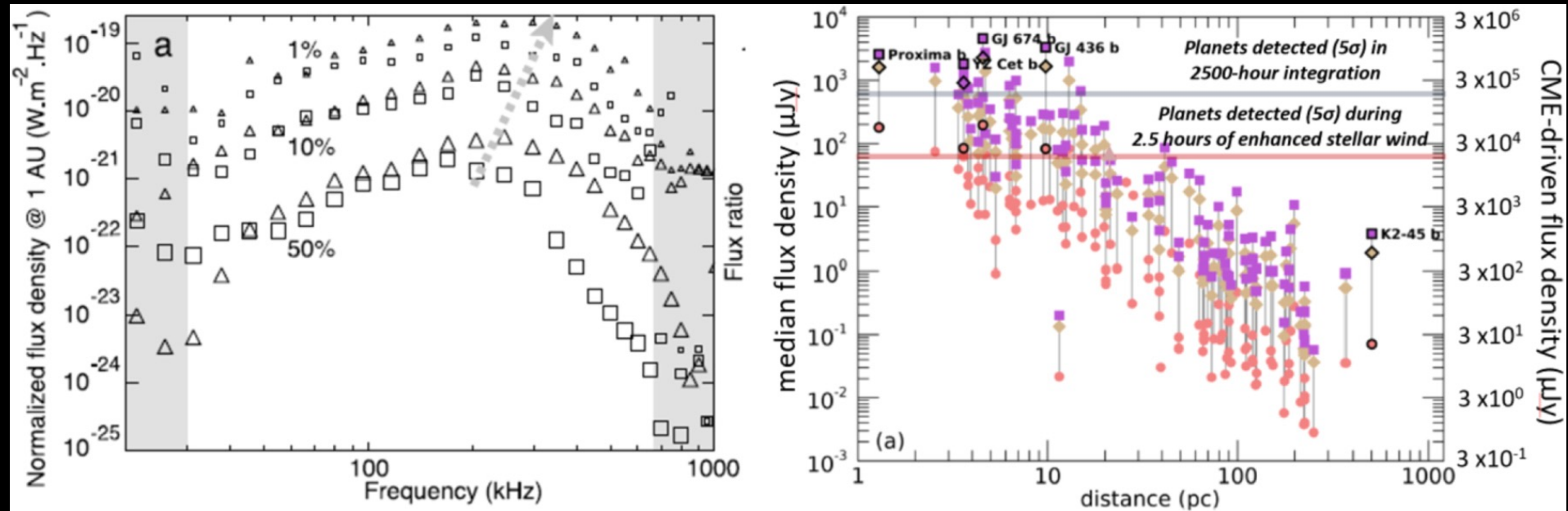
- imaging radio emission from coronal mass ejections (CME) beyond $2R_{\odot}$,
- monitor auroral radiation from the B-fields of Uranus and Neptune (not observed since Voyager)
- detect radio emission from stellar CMEs and the magnetic fields of nearby potentially habitable exoplanets

FARSIDE



(A): distribution of FARSIDE antennas on the lunar surface. Elevations derived from NASA LRO LOLA. (B): instantaneous u-v coverage for the antenna distribution shown in panel (A). (C): estimated emission from a solar CME shock front (Type II radio burst) at 6 MHz. The yellow disk is the approximate size and location of the Sun. (D): “cleaned” radio map of Type II burst in panel (C) as imaged via the FARSIDE array at 6 MHz with 1 minute integration. The white circle in the lower left is the FWHM of the synthesized beam.

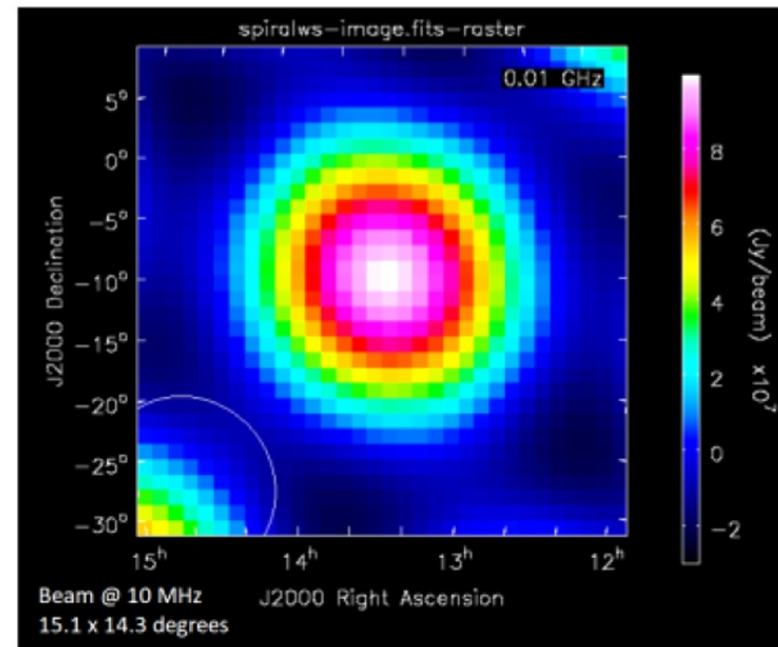
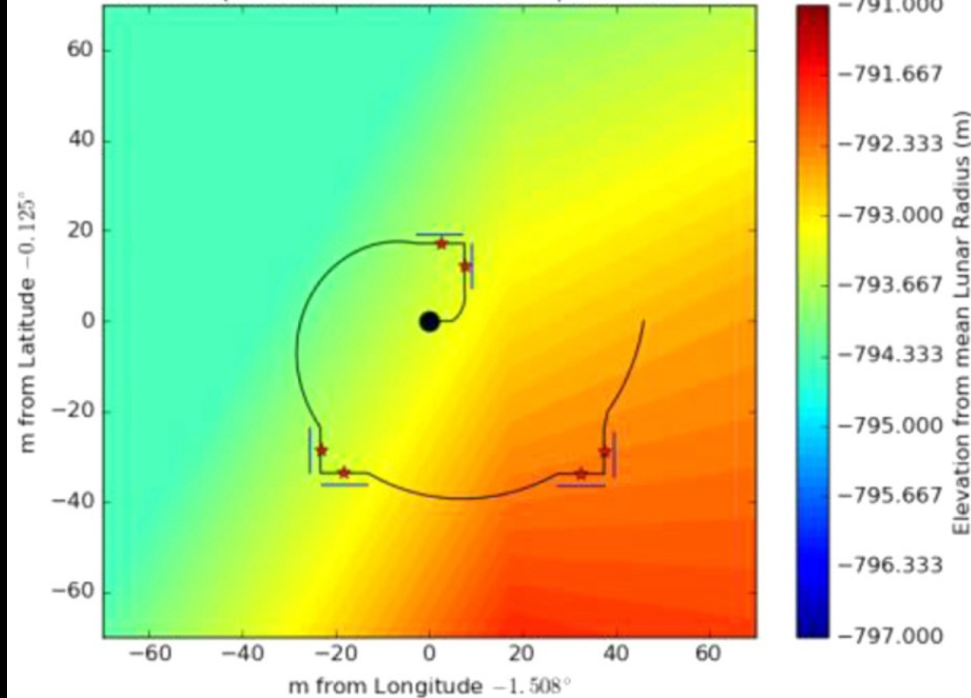
FARSIDE



Left: the radio spectrum of Earth's AKR for 50%, 10%, and 1% of the time. The flux density across the entire detectable band can vary by factors of a few hundred (Lamy et al. 2010). Right: the predicted average radio flux density at ~ 280 kHz of known exoplanets orbiting M dwarfs from Vidotto et al. (2019) assuming a magnetic field of 0.1 G (10% of Earth's magnetic field). Purple, yellow, and red data points reflect different models for the quiescent stellar wind. The horizontal gray line represents the 5σ detection limit (y-axis on left-hand side) on the median flux density for the auroral radio emission detectable from FARSIDE in a 2500 hr integration. The horizontal red line represents the 5σ detection limit (y-axis on right-hand side) in a 2.5 hr integration during enhanced stellar wind conditions, e.g., during a CME, assuming a similar degree of variability as observed for Earth's AKR. A large sample of planets, including some nearby candidate habitable planets (such as Proxima b), are detectable.

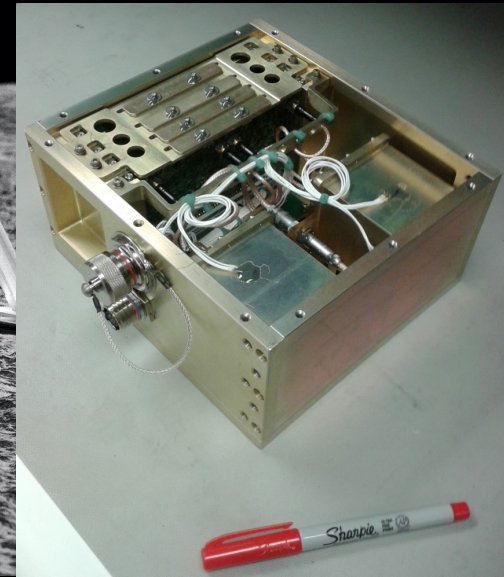
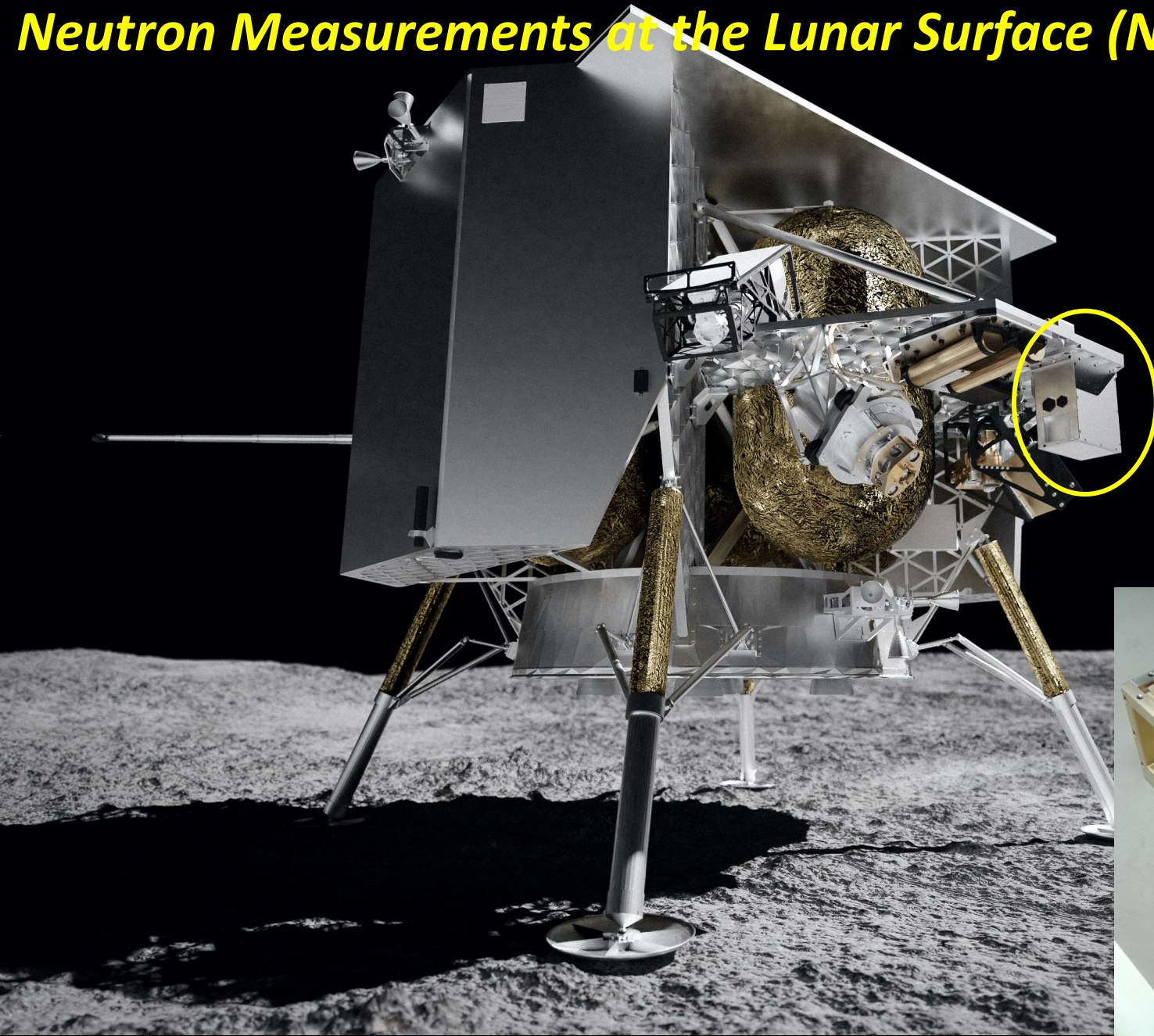
FAR SIDE

Elevation Map & Antenna Locations, Spiral Dist=199.8 m



With the distribution of three pairs of PRIME antennas in a 200 m spiral pattern on the lunar surface shown in the left panel, the resulting interferometric “dirty” image from a “snapshot” at 10 MHz in the right panel illustrates the clear detection of a 109 Jy point source as expected for a Type II solar radio burst. The white ellipse is the FWHM of the array beam.

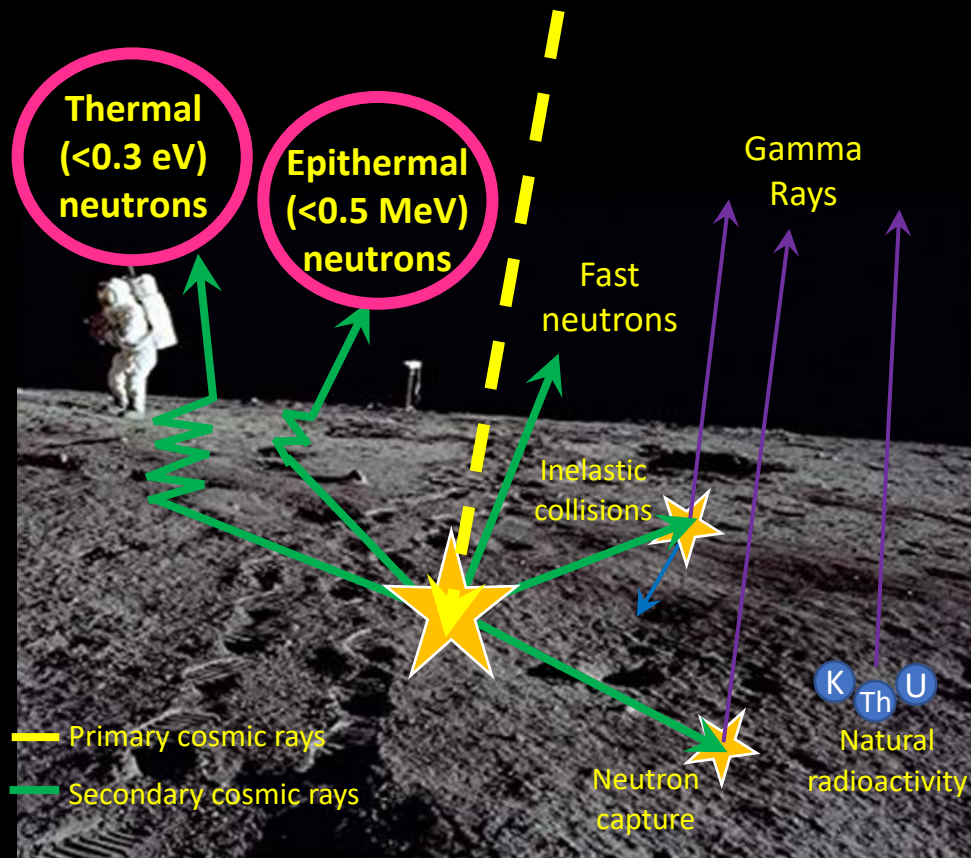
CLPS Task Order 2 Astrobotic, Neutron Measurements at the Lunar Surface (NMLS)



Neutron Spectroscopy

After Curran [2017]

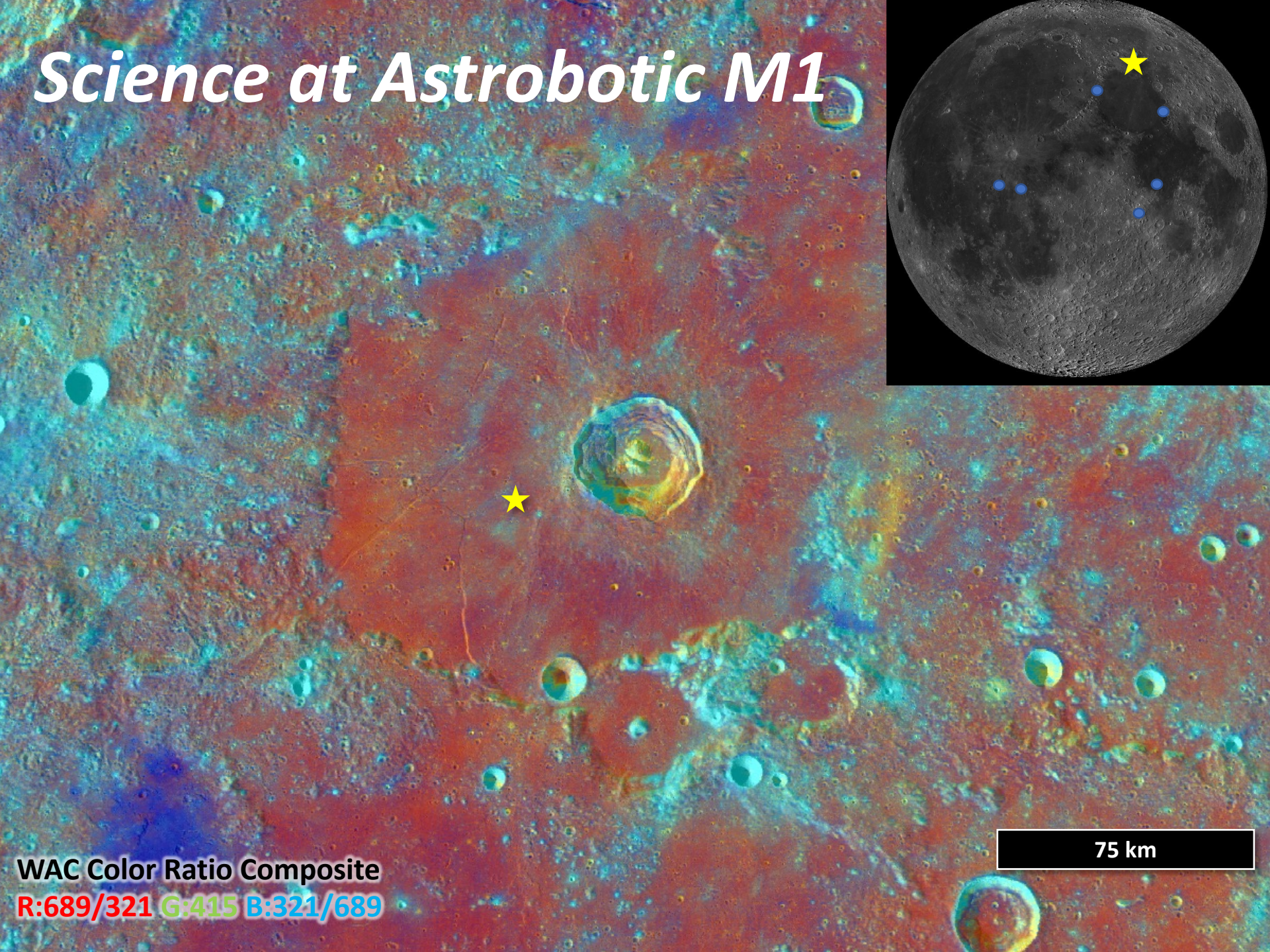
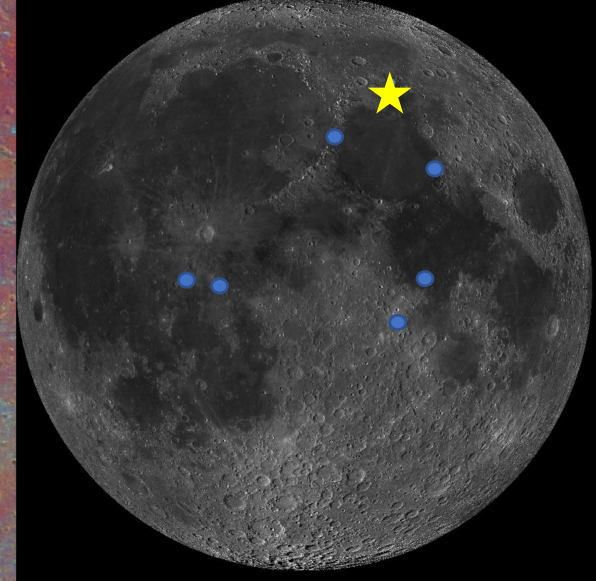
SEPs & GCRs (~1 GeV)



- “Epithermal neutrons”
 - medium energy
 - ~constant for most lunar compositions (except H).
- “Thermal neutrons”
 - low energy
 - absorption cross section increases by nuclei
 - is highly composition dependent (flux is large for Fe, Ti)
 - Flux is greater in mafic materials (mare basalts, Mg or Fe-rich, of igneous/volcanic origin, dark in color, olivine, pyroxene)
 - Flux is smaller in the Fe-poor highlands (farside).
- MSFC scintillator technology effectively discriminates between pulse shapes and distinguishes between neutron and gamma ray (as well as other false) triggers.

High value science opportunities exist for NMLS.

Science at Astrobotic M1

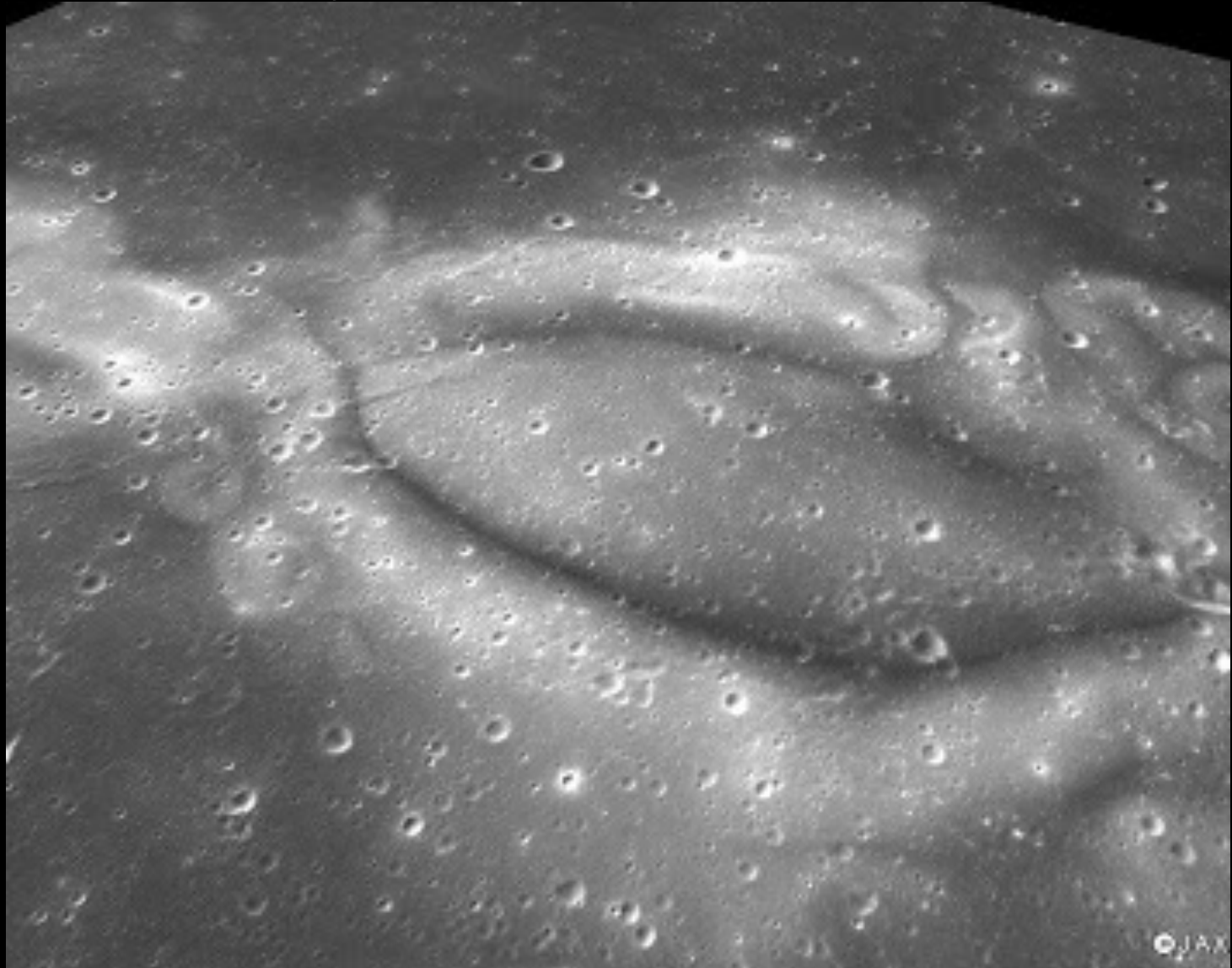


75 km

WAC Color Ratio Composite
R:689/321 G:415 B:321/689

CLPS PRISM 11 (CP11)

NASA delivery to Reiner Gamma in 2024



Big Science Questions

- Where are the polar volatiles and how did they get there?
 - What are the chemical and isotopic compositions of volatile deposits?
- How did the Moon form/evolve?
 - Sampling of ancient crust/mantle material, and geophysical measurements (seismometer/heat flow probe) will provide new insight into the lunar interior structure and composition, and of the Moon's geologic evolution.
- Are there rock types that we didn't sample in Apollo, and what can they tell us about the Moon's evolution?
- Can we use the Moon to understand the distribution and timescale of impacts and volcanism on the inner planets?
- Can we explore craters to understand the physics of impact cratering, the most prevalent geologic process in the Solar System?

Lunar Science by 2024

A black and white photograph of a lunar surface. In the foreground, a robotic arm with a bucket is visible, having just deposited a sample of lunar soil. The surface is covered in fine-grained regolith and small rocks. In the background, the dark, cratered landscape of the Moon stretches towards the horizon under a bright sky.

Polar Landers and Rovers

- First direct measurement of polar volatiles, improving understanding of lateral and vertical distribution, physical state, and chemical composition
- Provide geology of the South-Pole Aitken basin, largest impact in the solar system

Non-Polar Landers and Rovers

- Explore scientifically valuable terrains not investigated by Apollo, including landing at a lunar swirl and making first surface magnetic measurement
- Using PI-led instruments to generate Discovery-class science, like establishing a geophysical network and visiting a lunar volcanic region to understand volcanic evolution

Orbital Data

- Deploy multiple CubeSats with Artemis 1
- Potential to acquire new scientifically valuable datasets through CubeSats delivered by CLPS providers or comm/relay spacecraft
- Global mineral mapping, including resource identification, global elemental maps, and improved volatile mapping

In-Situ Resource Initial Research

- Answering questions on composition and ability to use lunar ice for sustainment and fuel

Science After 2024

Human and Robotic Missions Provide Unique Science Opportunities

On Gateway

- Deep space testing of Mars-forward systems
- Hosts groundbreaking science for space weather forecasting, full-disc Earth observation, astrophysics, heliophysics, lunar and planetary science
- Mars transit testbed for reducing risk to humans

Surface Exploration

- Understanding how to use in-situ resources for fuel and life
- Revolutionizing the understanding of the origin and evolution of the Moon and inner solar system by conducting geophysical measurements and returning carefully selected samples to Earth
- Studying lunar impact craters to understand physics of the most prevalent geologic process in the solar system, impact cratering
- Setting up complex surface instrumentation for astrophysics, heliophysics and Earth observation
- Informing and supporting sustained human presence through partial gravity research in physical and life sciences, from combustion to plant growth

Surface Telerobotics to Provide Constant Science

- Sending rovers into areas too difficult for humans to explore; rovers can be teleoperated from Earth to maximize the scientific return



Questions?

<https://intern.nasa.gov/>



Image Source: NASA Apollo 8, Bill Anders



EXPLORE MOON_{to}MARS

MOON LIGHTS THE WAY

<https://www.nasa.gov/clps>

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