TRANSFORMATIVE SCIENCE FROM THE MOON: ASTROPHYSICS, COSMOLOGY, & HELIOPHYSICS

Jack Burns
University of Colorado Boulder

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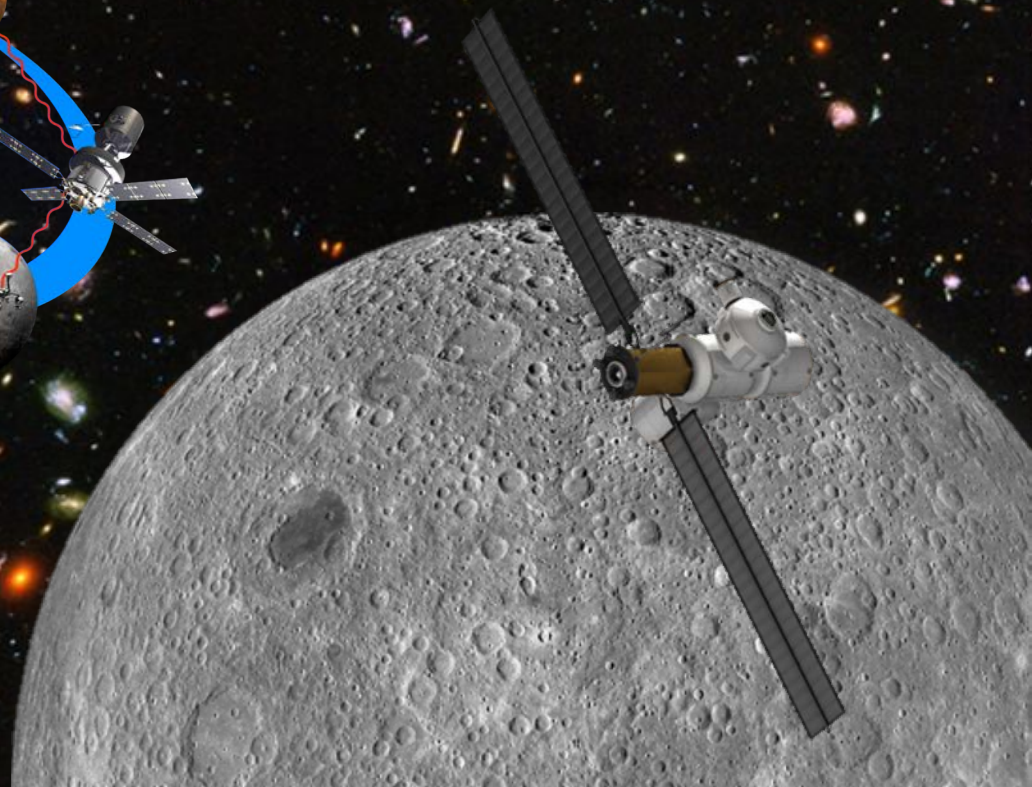
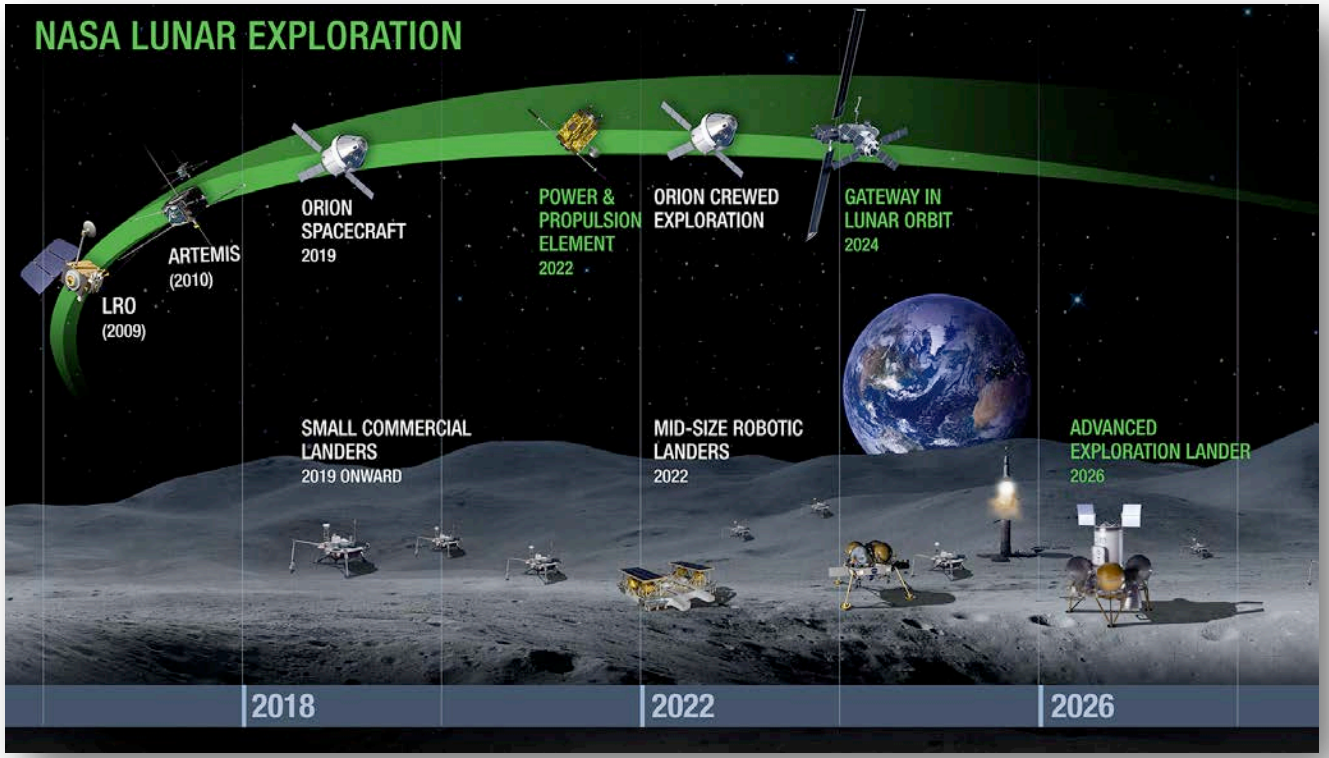


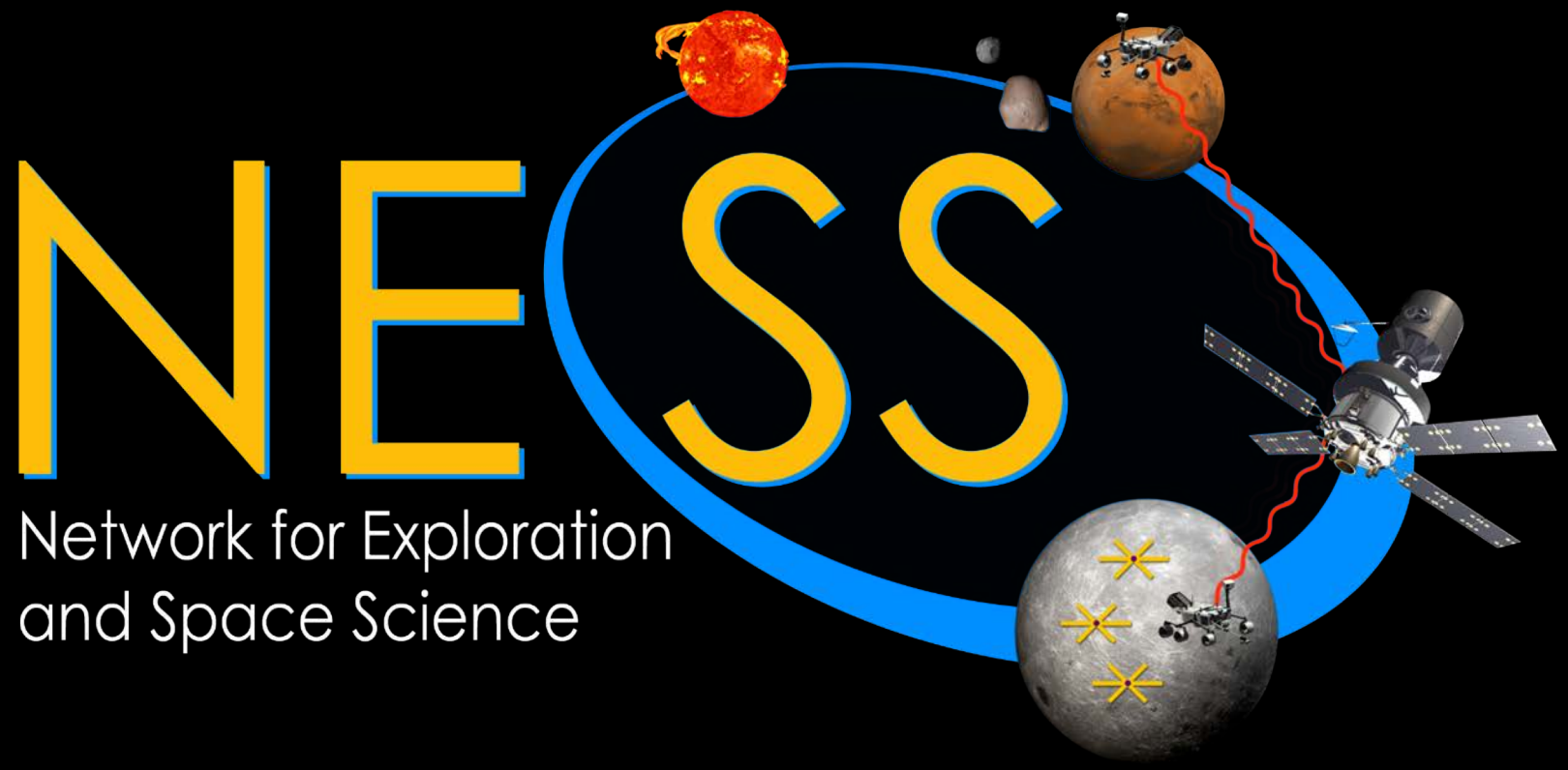
Joint Meeting of NAC Science & HEO Committees, 28 August 2018

Outline

1. Low Frequency Radio Heliophysics.
2. Magnetospheres & Space Weather Environments of Extrasolar Planetary Systems.
3. Astrophysics and Cosmology.
   a) Deployment UV/Visible telescope at Lunar Gateway.
   b) 21-cm Hydrogen Cosmology.
4. Implementation Strategy utilizing Low Latency Surface Telerobotics.



Low Frequency Radio Heliophysics



Co-Investigators:
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Collaborators:
Bill Farrell, NASA GSFC
Dan Baker, U. Colorado
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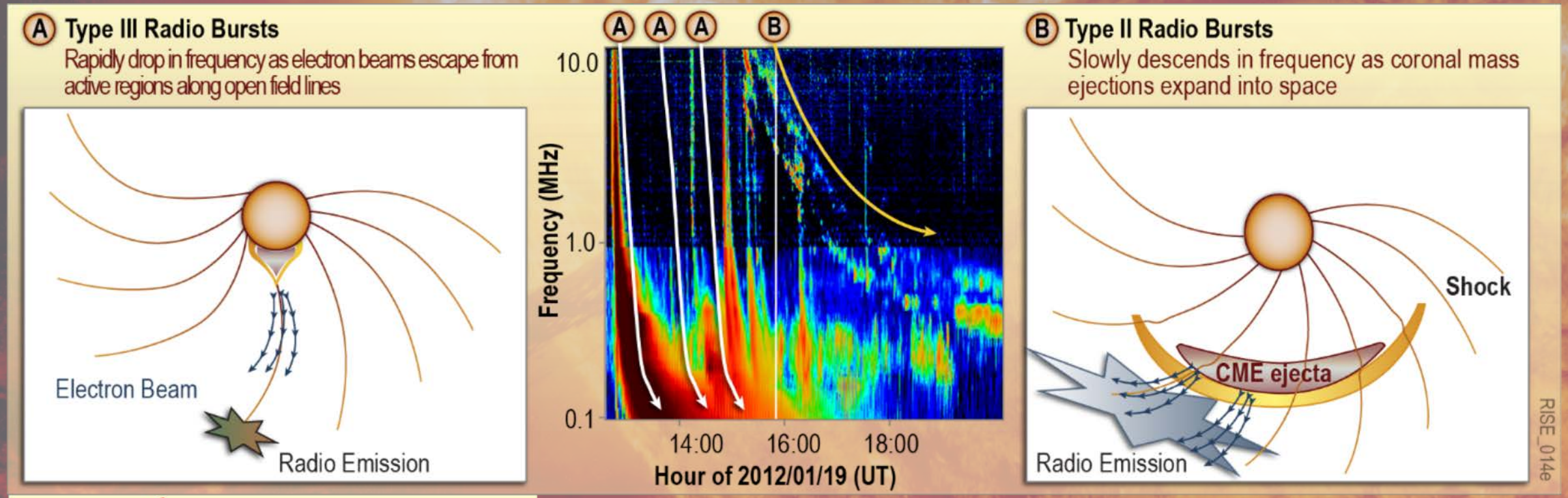
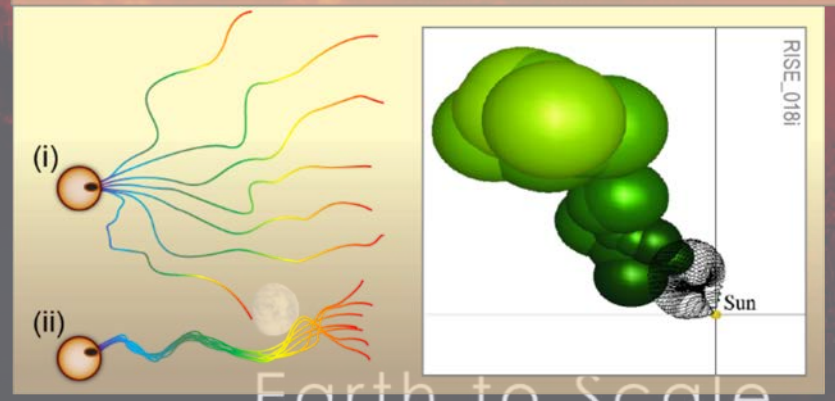
Solar Type II & III Bursts



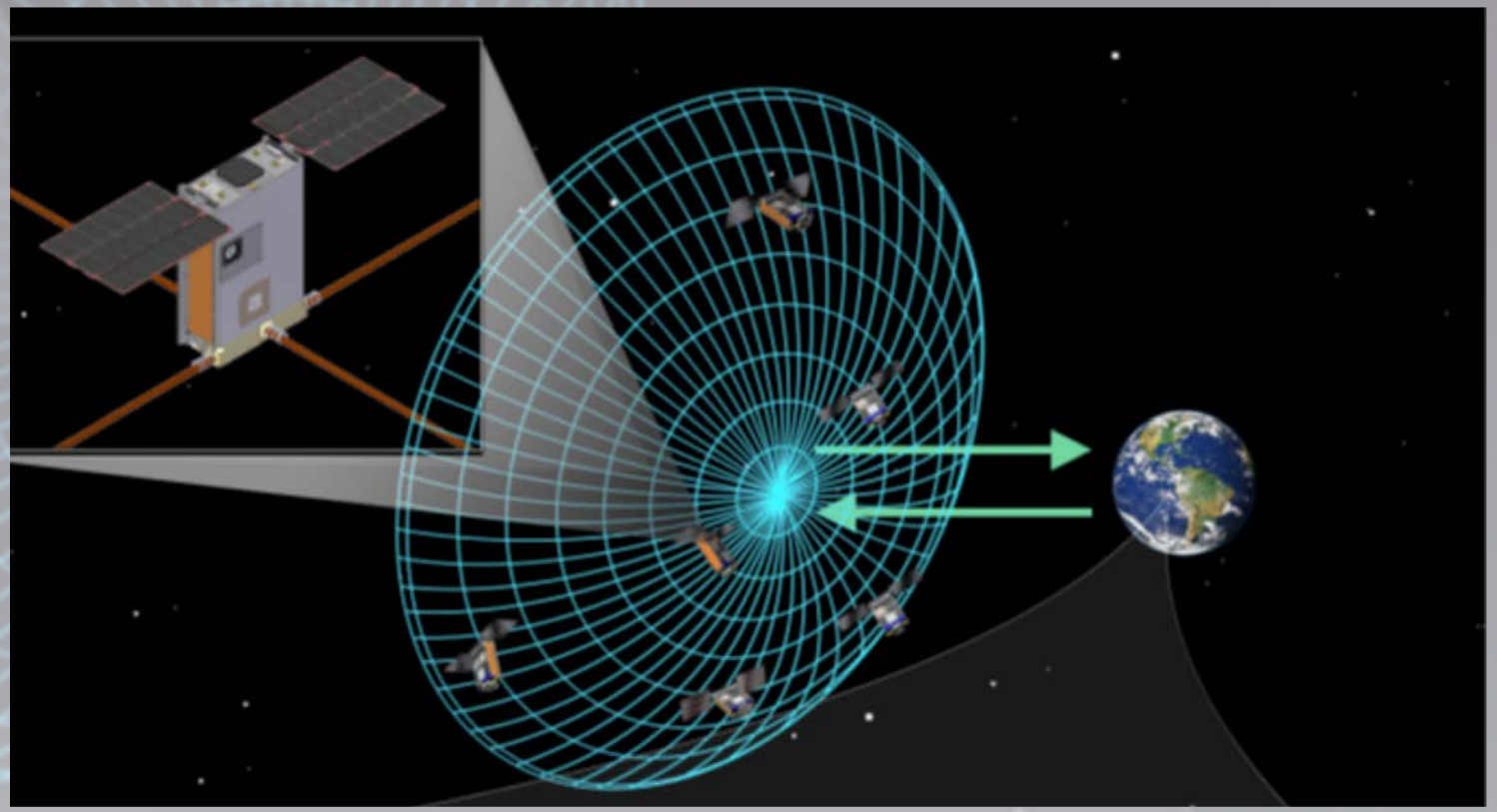


Figures from SunRISE Concept Study

Bougeret, J.-L., M. L. Kaiser, P.J. Kellogg, et al., "WAVES: The Radio and Plasma Wave Investigation on the WIND Spacecraft", *Space Sci Rev*, 71, 5, 1995.

SunRISE – Earth Orbiting Array

- SunRISE – Sun Radio Interferometer Space Experiment
- Heliophysics Explorers Mission of Opportunity
- Currently in Phase A
- Will launch 2022 if funded
- 6 CubeSats in GEO Graveyard Orbit
- Track Bursts to 20 Rs



P.I. Justin Kasper, U. Michigan

Legend

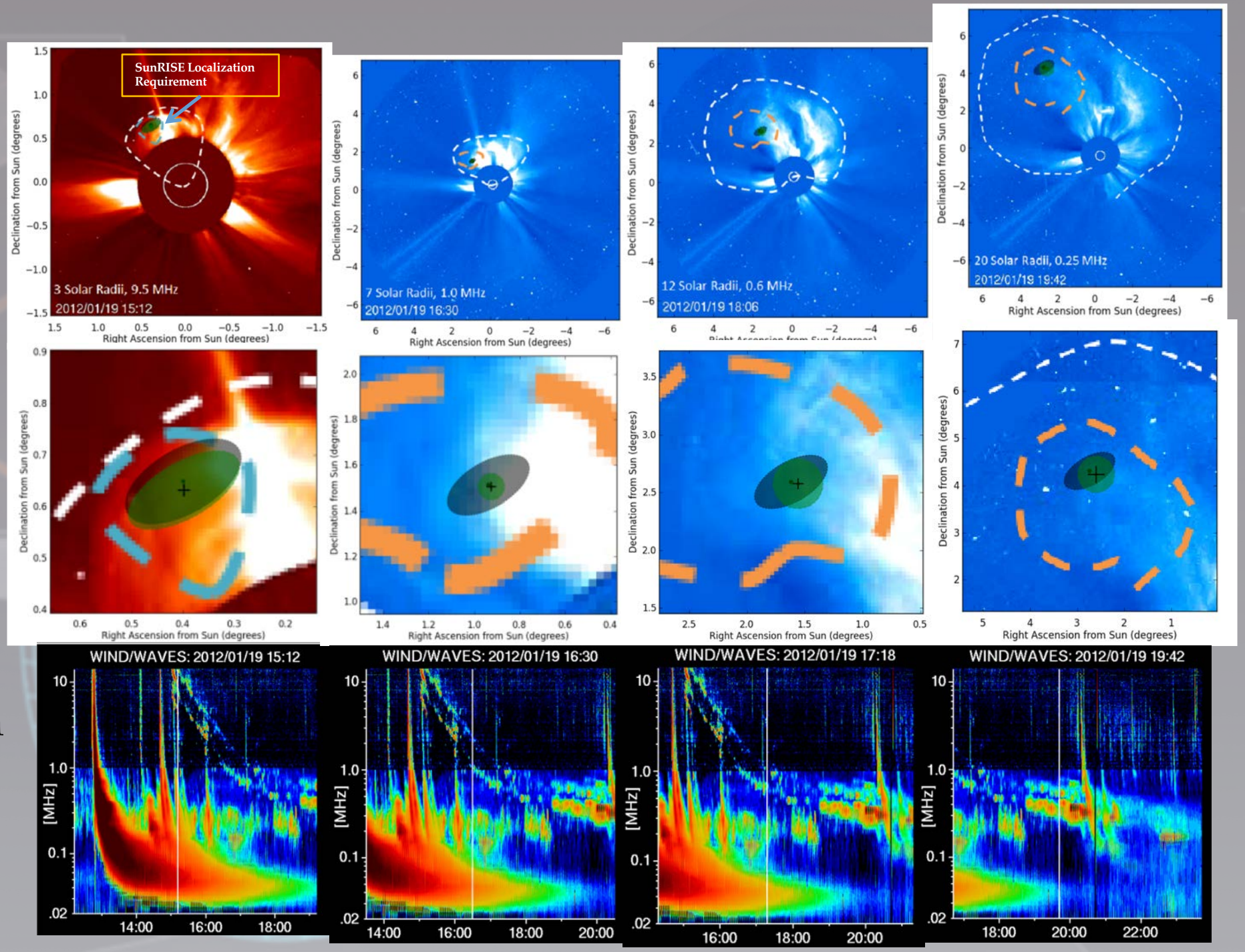
Big Dashed Line:
All Disturbed

Small Dashed Line:
1/3 Size of CME
Base Requirement

Black Ellipse:
Truth Input

Green Ellipse:
Array Reconstruction

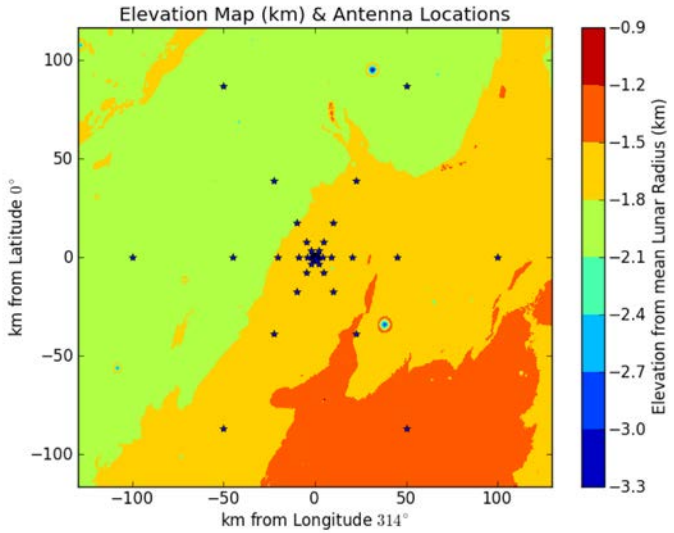
Error Bars:
1 sigma 5 S/C error
Over 80 Trials



Requirements for imaging these radio sources from the lunar surface

Table 3.4.1. Summary of ROLSS parameters

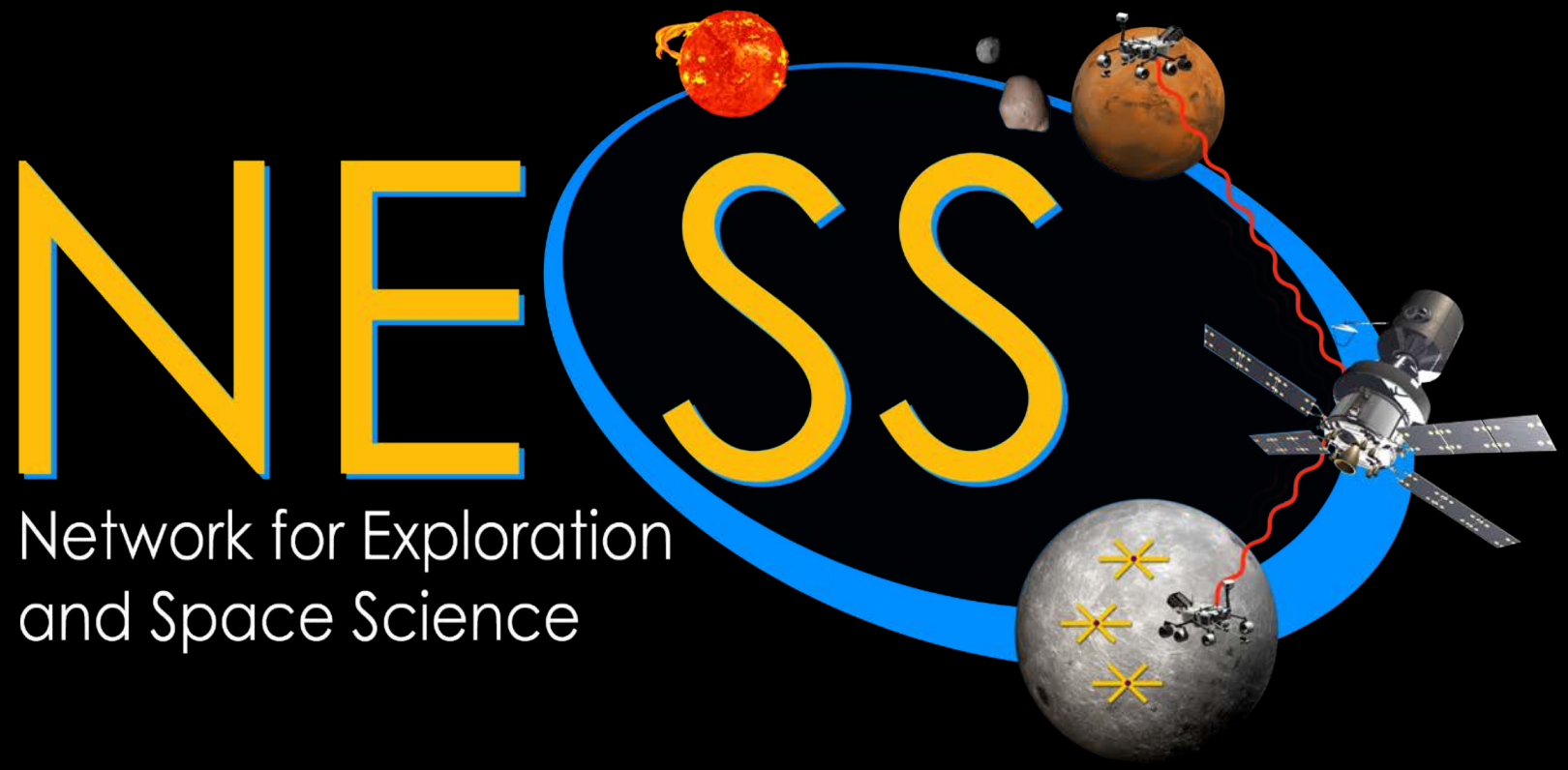
Parameter	Value	Comment
Wavelength (Frequency)	30–300 m (1–10 MHz)	• Matched to radio emission generated by particle acceleration in the inner heliosphere • Provide context for observations during Solar Probe Plus perihelion passes • Detect lunar ionosphere • Operate at frequencies below the terrestrial ionospheric cutoff
Angular Resolution	2° (at 10 MHz)	• Localize particle acceleration sites of CME shocks and Type III solar bursts • Order of magnitude improvement from present
Bandwidth	≥ 100 kHz	Track time-evolution of particle acceleration
Minimum Lifetime	~1 year	Obtain measurements during several solar rotations; avoid solar minimum



Radio Heliophysics Summary

- Solar radio bursts at frequencies < 20 MHz have never been imaged.
- The timing and location of the bursts provides an indication of energetic particle acceleration, and therefore, the potential of space weather alerts.
- Imaging the bursts will also provide data on the locations of electron acceleration, answering magnetic field configuration and other questions.
- Radio observatory antennas on the lunar surface will also be large dust detectors, especially if the unrolled-polyimide antenna substrate is used.
- We realized during the proposal development that a near side radio array might be able to observe synchrotron radio emissions from the Earth's radiation belts. This emission is also controlled by space weather events.
- Requirements for the pathfinder lunar surface radio telescope are modest, except for surviving the thermal environment, which includes surviving 14 days of lunar night. OK, maybe getting to the surface is still an issue…

Magnetospheres & Space Weather Environments of Extrasolar Planets



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Credit: KISS/Caltech

Is magnetic activity important for defining habitability?
Can we directly detect CMEs and planetary magnetic fields?
<u>Yes – with radio observations</u>

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Low Frequency Radio Emission

Type III radio emission associated with CMEs

Planetary auroral radio emission

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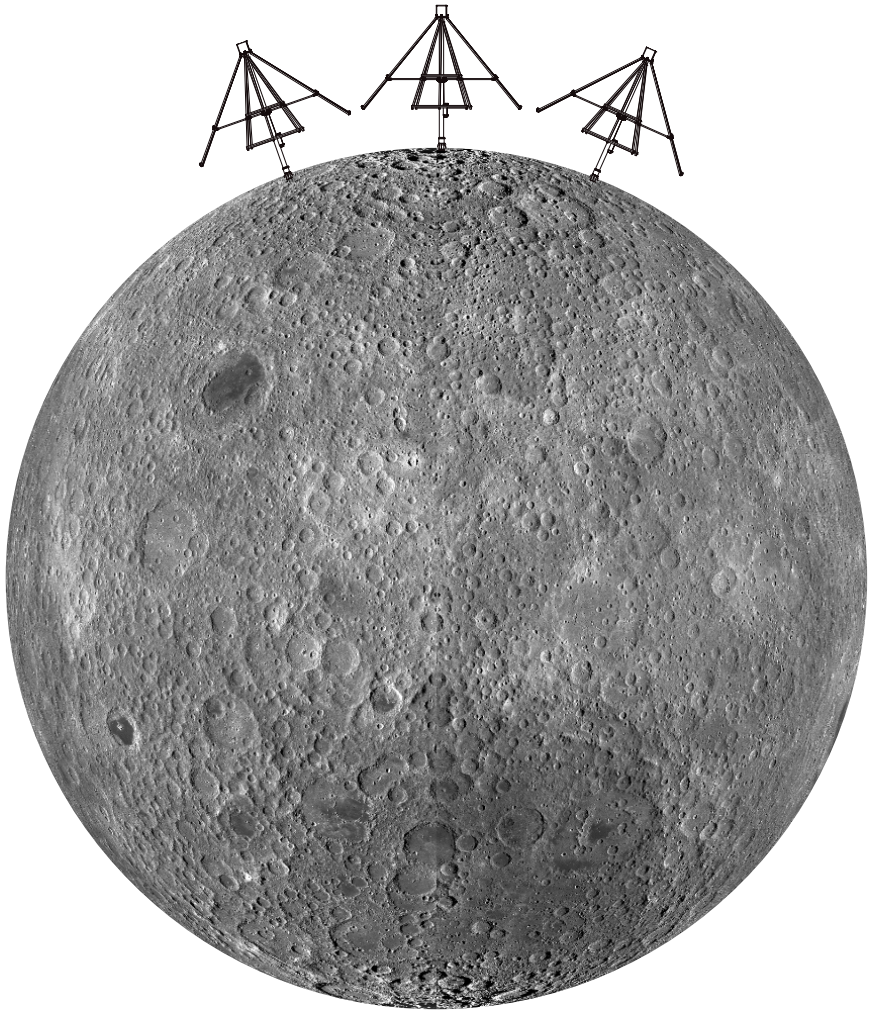
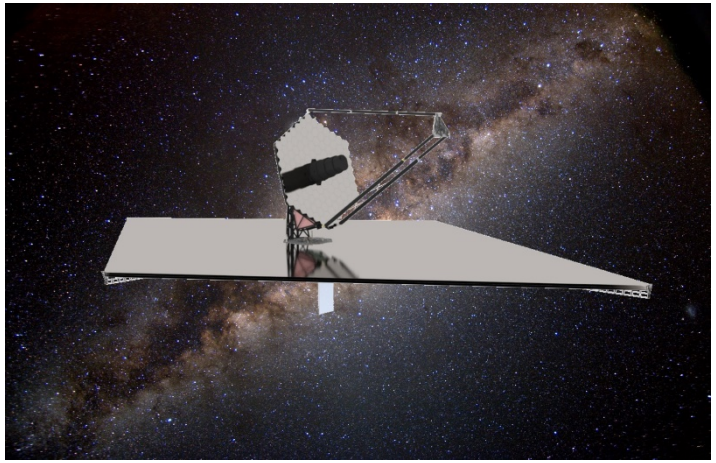
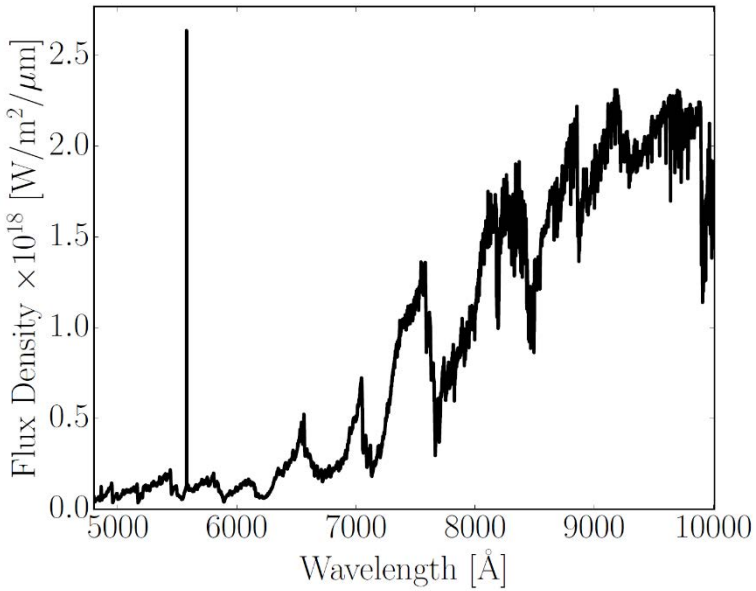
Triggered Alerts from a Lunar Array







Simulated high-resolution spectrum of Proxima Cen b with 0.1 TW auroral emission at 5577 Å (Luger et al. 2017)

Extrasolar planets: Summary

Understanding the impact of stellar activity and the presence of planetary magnetic fields is becoming increasingly important for defining planetary habitability

Low frequency radio observations are key

The long-term future is from the lunar far-side

Targeted searches are computationally low-cost but limited

Multiplexed searches require significant in-situ computational resources

Triggered searches for biosignatures present an exciting possibility

Astrophysics & Hydrogen Cosmology

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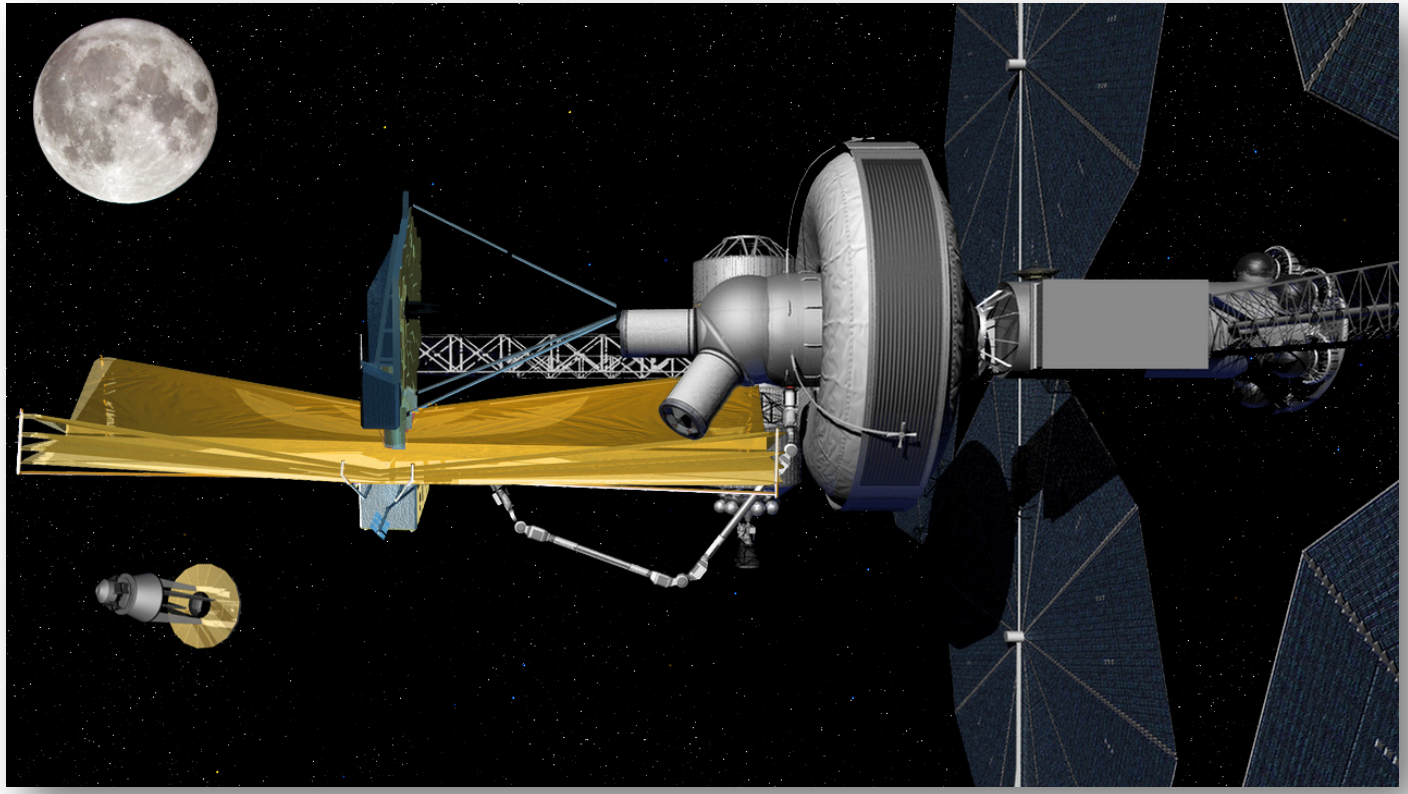
GATEWAY TO DEEP SPACE
and
GATEWAY TO THE SEARCH FOR LIFE IN THE GALAXY

The lunar Gateway is not just the gateway to the Moon, Mars, and beyond, but it can also be the gateway to the search for life in the Galaxy.

Illustration credit: Nick Siegler and the FASST Team; JPL/Caltech, NASA, ATLAST, DSG adapted from Boeing, Nancy Kiang (NASA GISS), Lizbeth Barrios de la Torre (JPL/Caltech)

Potential Capability Needs of the Gateway

- Proximity operations (docked during assembly; not docked during servicing)
- Autonomous and dexterous external robotic arms capable of assembling and servicing
- Berthing points for unpressurized cargo containers



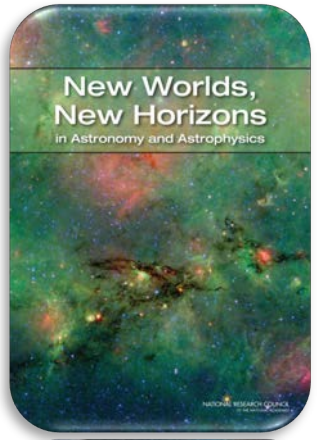
NASA

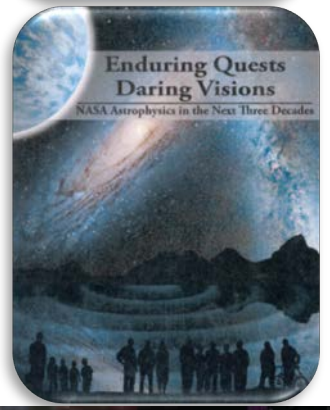
- Telerobotic operations from both Earth and the DSG
- Astronaut EVAs
- Defined power, propulsion, attitude control
- Quiescent environment
- Photogrammetry capabilities

Astrophysics Decadal Survey & *NASA Astrophysics Roadmap* identify Cosmic Dawn & Dark Ages as a top Science Objective

- ***New Worlds, New Horizons (NRC 2010):*** "A great mystery now confronts us: When and how did the first galaxies form out of cold clumps of hydrogen gas and start to shine—when was our cosmic dawn?"

- ***NASA Astrophysics Division Roadmap (2013):*** How Does our Universe Work?
  - **Small Mission:** "Mapping the Universe's hydrogen clouds using 21-cm radio wavelengths via a *lunar orbiter* observing from the farside of the Moon".
  - **Visionary Era:** "*Cosmic Dawn Mapper* (21-cm lunar surface radio telescope array) … Detailed map of structure formation in the Dark Ages via 21-cm observations".





"What were the first objects to light up the Universe and when did they do it?" **NRC Astro 2020 Decadal Survey, New Worlds, New Horizons.**

NETHERLANDS-CHINA LOW-FREQUENCY EXPLORER (NCLE)

- Will characterize the RFI environment in deep space at Earth-Moon L2.
- Will serve as precursor for future Hydrogen Cosmology missions and radio interferometry.
- Will attempt to detect CMEs from the Sun.
- 3 orthogonal, monopoles of 5-m length. Frequencies: 1-80 MHz.
- NESS collaborators Heino Falcke and Marc Klein-Wolt are the Dutch leads for this project.

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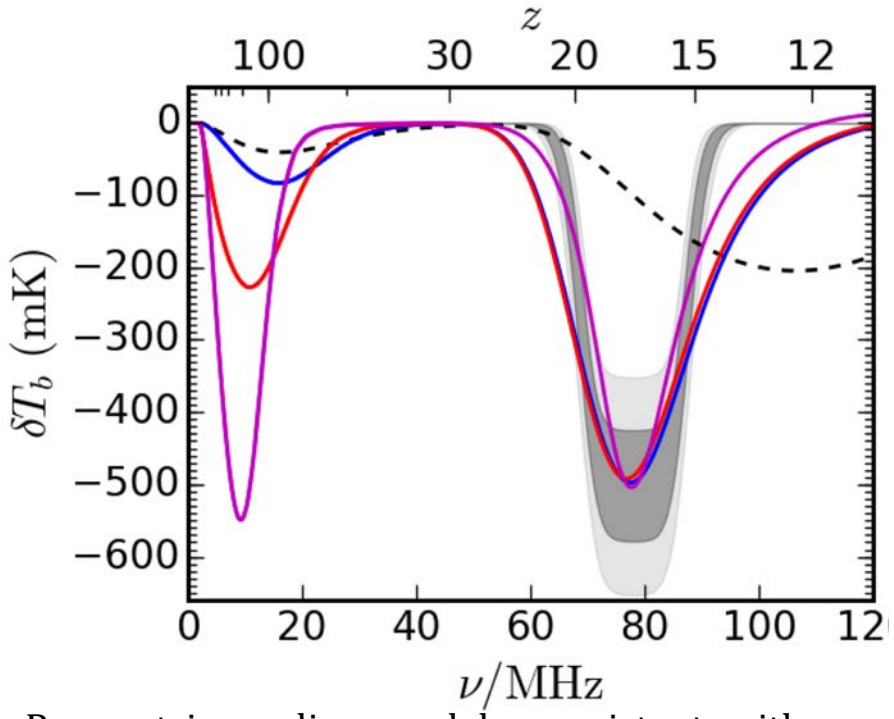
A NASA-funded SSERVI Team

Dark Ages Polarimeter PathfindER (DAPPER)

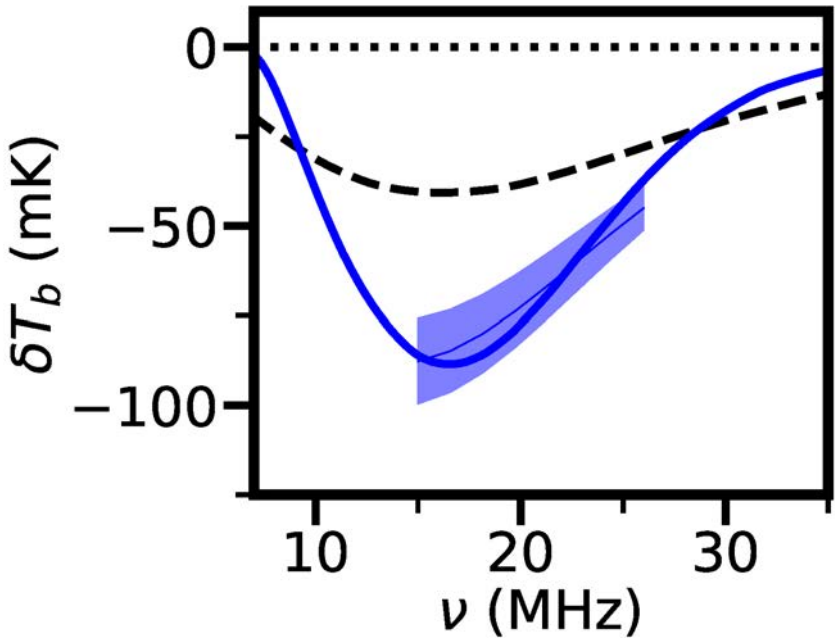
Burns et al. 2017, *A Space-based Observational Strategy for Characterizing the First Stars and Galaxies Using the Redshifted 21 cm Global Spectrum*, ApJ, 844, 33.

The Dark Ages Polarimeter PathfindER (DAPPER): Probing Dark Matter in the Dark Ages – P.I. Jack Burns, U. Colorado

Science Objective: Search for deviations from the standard model of cosmology, possibly produced by dark matter, via measurements of the low radio frequency absorption trough at ~15-30 MHz (93≥z≥46) in proximity to the Lunar Gateway.
Technical Implementation: 7-m diameter cross-dipole antenna on SmallSat to measure polarization of galactic foreground (heritage: WIND/WAVES); low noise amplifiers & dual channel receiver to measure all 4 Stokes parameters. (Based on Parker Solar Probe FIELDS instrument).



Parametric cooling models consistent with new EDGES results (grey bands) predict deep absorption troughs at <20 MHz which we will observed by DAPPER.



Estimated uncertainties for DAPPER observations using Machine Learning, Pattern Recognition, & Training Sets.

3 locations for DAPPER will be studied: (1) on the Gateway, (2) released from the Gateway, (3) delivered to low lunar orbit by Gateway tug.

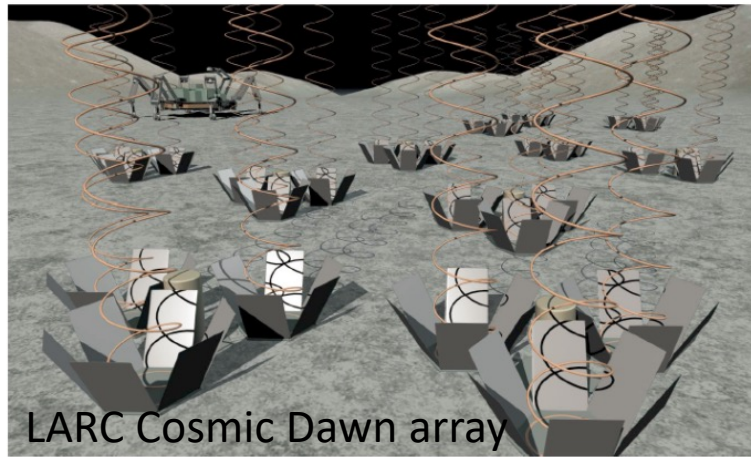
21-cm Dark Ages Science

Science Traceability Matrix			
Decadal Science Goals	**Science Objectives**	**Science Measurements**	**Instrument Requirements**
1) What is the nature of inflation?	1) Are primordial matter density perturbations non-Gaussian? What is the value of f_{NL}?	1) Power spectrum of redshifted 21cm absorption fluctuations before stars 2) Frequency range approx. 10-40 MHz ($50<z<100$) 3) Angular modes between 1 and 10 degrees 4) Spectral modes between 0.05 to 4 MHz	1) Full Stokes aperture synthesis array on lunar farside (to avoid ionosphere and RFI) with: * 400,000 m^2 area * 1 km baselines * Full-sky imaging 2) High-precision bandpass and beam calibration for foreground removal 3) Hardware that is radiation and thermally tolerant to survive the lunar environment 4) Deployer for chosen antenna design
	2) What are the cosmological parameter values?		
2) What is the nature of dark matter?	3) What is the temperature evolution of baryons after recombination?		

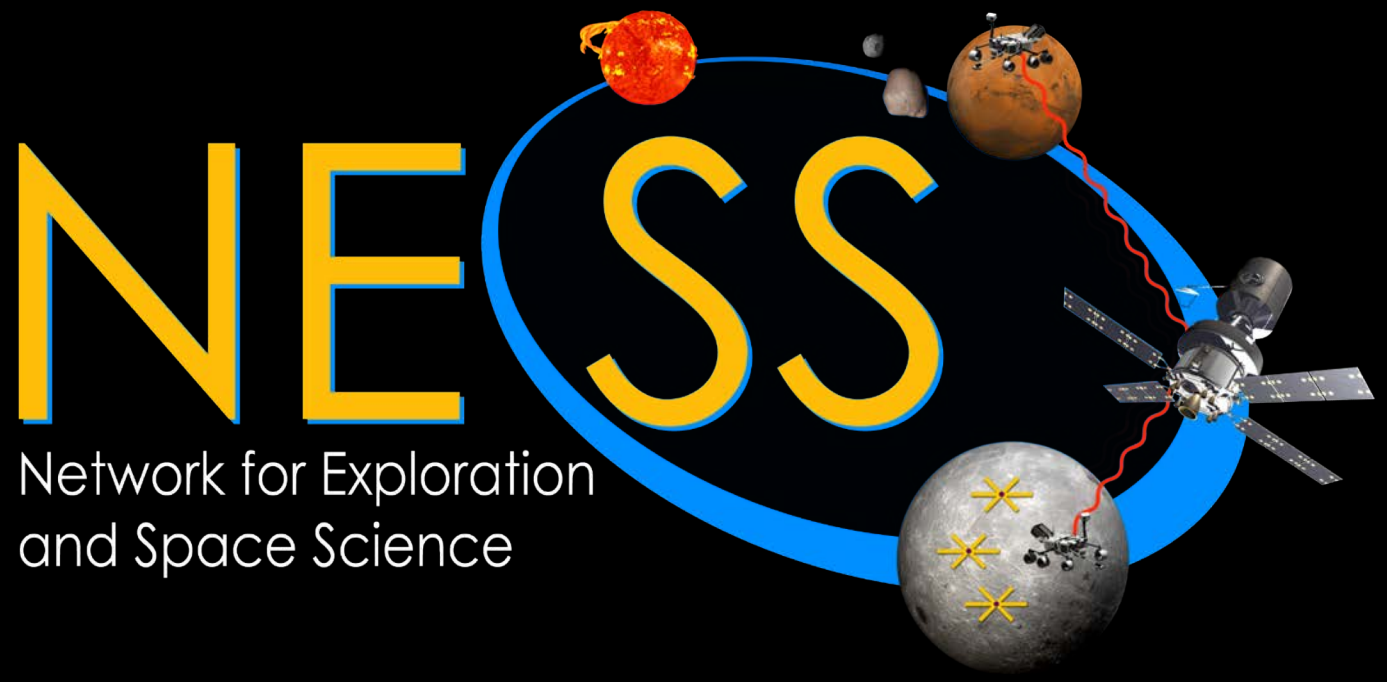
Notional pathfinder array – 1%

- Lunar farside
- Frequency band:
  - 1-20 MHz
- 1 Jy sensitivity:
  - 100 dipole-like antennas
- 1 degree resolution:
  - 1 km baselines
- Data rate:
  - 4 GB/s (raw)
- Power estimate:
  - Analog 100 elements: <20 W
  - Digital processing: 10-100 W
- Lifetime:
  - 1-5 years
- Mass and volume target/estimate:
  - 10^4 cm^3 per antenna = 1 m^3 total
  - 10 kg per antenna = 1000 kg total


DALI / ROLSS


LARC Cosmic Dawn array

Low Latency Surface Telerobotics



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Engineering Undergraduate Students:
Alex Sandoval, U. Colorado
Arun Kumar, U. Colorado

Lunar Robotics Support

The Gateway could provide infrastructure for lunar robotics

- **Communications relay**: provide (or increase) link availability and bandwidth to the surface – particularly polar regions and the far side
- **"Orbital computing"** (space equivalent of "cloud computing")
  - Off-load processing from rover – potentially much higher performance
  - Off-board storage from rover – for later triage, downlink, or retrieval
- **Mapping from orbit**: provide site maps
- **Positioning** & **timing**: assist rover localization
- **Power beaming**: provide supplementary and survival energy
- **Remote sensing**: complement surface level data collection
- **Sample return cache**: intermediate location for high-grading
- … and more …

Lunar Mission Simulation (2013)

"Surface Telerobotics" Project

- Simulation of the "Orion at Earth-Moon L2 Lagrange" concept
- Astronauts in the International Space Station (ISS)
- K10 planetary rover at NASA Ames
- Data comm via satellite relay with short delay (**750 msec round-trip**)
- Asynchronous bandwidth (**3 Kbps downlink, 800 Kbps uplink**)

ISS Expedition 36 testing

June 17, 2013 – **C. Cassidy**, survey

July 26, 2013 – **L. Parmitano**, deploy

Aug 20, 2013 – **K. Nyberg**, inspect

SURVEY

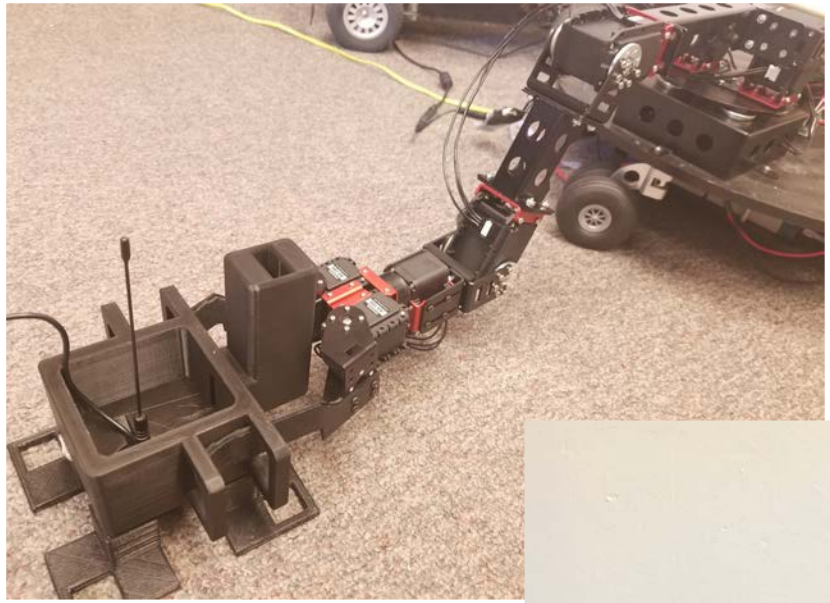
DEPLOY

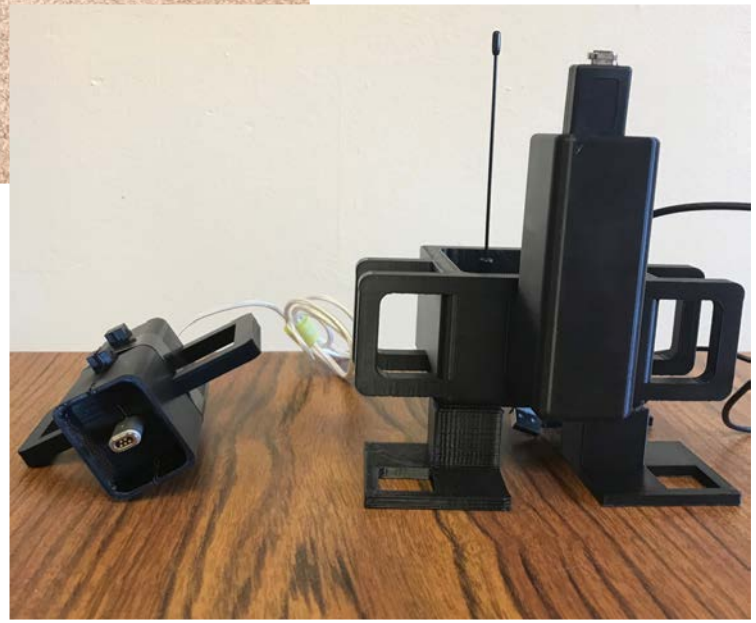
INSPECT

- **Human-robot mission sim**: site survey, telescope deployment, and inspection
- **Telescope proxy**: Kapton polyimide film roll (no antenna traces, electronics, or receiver)
- **3.5 hr per crew session** ("just in time" training, system checkout, ops, & debrief)
- **Robot ops**: manual control (discrete commands) and supervisory control (task sequence)

Burns et al. 2018, *Science on the Lunar Surface Facilitated by Low Latency Telerobotics from a Lunar Orbiting Platform-Gateway*, Acta Astronautica, in press, arXiv:1705.09692.

Assembly of Radio Telescope Elements





- Radio Telescope Assembly
  - Construct a simple radio array telescope
  - Receive radio frequencies for data processing
  - Maximize situational awareness from video feedback
  - Robotic arm motion capabilities
- Connect magnetic micro USB to power and transmit data from antenna
- Using 3D printed case and gripper to aid the robotic arm
- Demonstration of how a radio telescope could be assembled on the lunar farside

A. Sandoval, A. Kumar, B. Mellinkoff, J. Burns

Teleoperated Assembly of Radio Telescope

University of Colorado Boulder
Arun Kumar
Benjamin Mellinkoff
Alexander Sandoval

LOCKHEED MARTIN

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VIRTUAL REALITY SIMULATION TESTBED:
IMPROVING SURFACE TELEROBOTICS FOR THE LUNAR GATEWAY

ATLAS INSTITUTE

IRON LABORATORY

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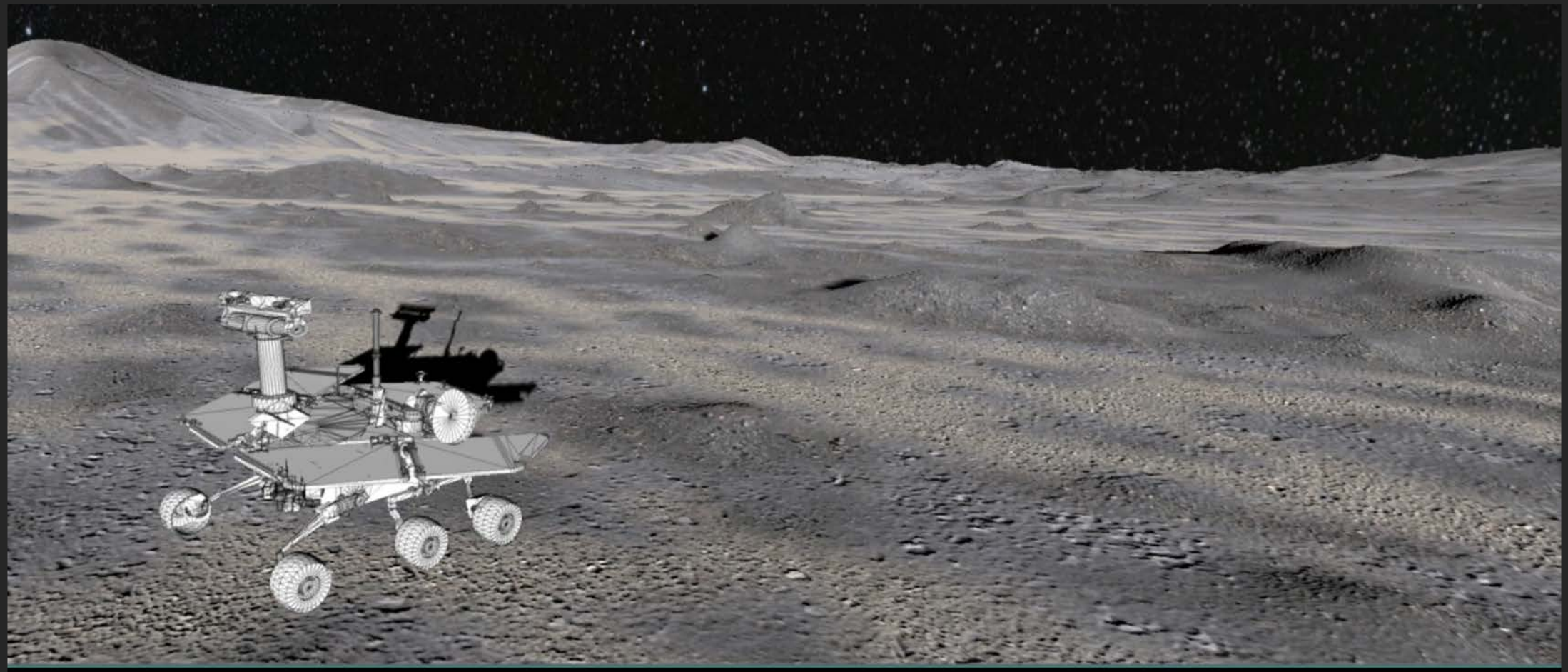
Michael Walker, Jack Burns, & Daniel Safir

ROVER TELEOPERATION via VR and AR



Summary

- There is much promising, transformative science from the Moon in astrophysics and heliophysics using the anticipated infrastructure from the Lunar Gateway and the lunar surface.
- Arrays of low frequency antennas at <10 MHz, initially on the lunar nearside, will provide the location and timing of radio bursts associated with CMEs, provide location of electron acceleration and magnetic field configurations, and serve as space weather alerts.
- Sensitive low frequency radio observations from the lunar farside can characterize space weather and magnetospheres in exoplanetary systems to probe habitability.
- The Gateway has promise to facilitate construction of large aperture UV/visible telescopes to characterize habitable planets.
- Hydrogen cosmology from the Moon has unique potential to characterize the first stars and galaxies, and to investigate dark matter in the Dark Ages.
- Teleoperation of rovers on the lunar farside by astronauts aboard the Gateway can be used to assemble low frequency radio telescopes even before astronauts reach the surface.

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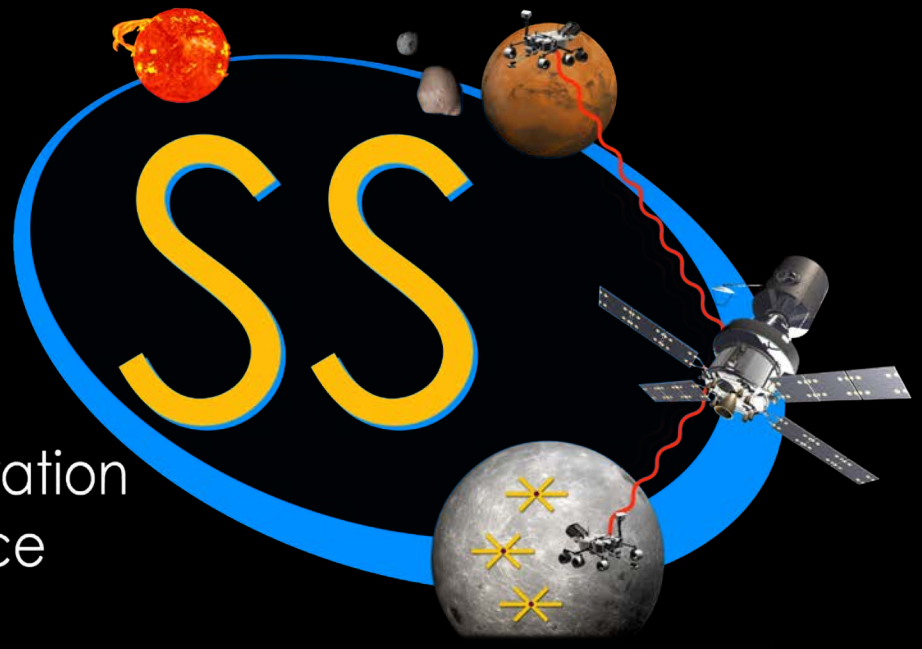

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NASA

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ASU

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Ball Aerospace

Lockheed Martin