DARE
Low Frequency Radio Astronomy From Space
Jack Burns
University of Colorado Boulder

U.S. Radio/Millimeter/Submillimeter Science Futures III
Lunar Farside: No RFI or Ionosphere!
Astrophysics Decadal Survey & NASA Astrophysics Roadmap identify **Cosmic Dawn** 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.**
The 21-cm Global All-Sky Signal
The 21-cm Monopole Reveals the Birth & Characteristics of the First Stars & Galaxies

\[ \delta T_B = 25x_{HI} \left( \frac{1+z}{10} \right)^{1/2} \left( 1 - \frac{T_{CMB}}{T_S} \right) \text{mK} \]

B: ignition of first stars
- When did the First Stars ignite?
- What were their characteristics?
- Is there evidence for exotic physics (e.g. Dark Matter decay) in the Dark Ages?

C: heating by first black holes
- When did the first accreting black holes turn on? What were their characteristics?

D: the onset of reionization
- What was the history of Reionization in the early Universe?

DARE Project Team

Principal Investigator: Jack Burns, University of Colorado Boulder
Observatory Project Management: Ball Aerospace & Technologies Corp.: W. Purcell & D. Newell

Science Co-Investigators:
Robert MacDowall, NASA GSFC, Project Scientist
Richard Bradley, NRAO, Deputy Project Scientist
Judd Bowman, Arizona State University
Anastasia Fialkov, CfA
Steven Furlanetto, UCLA
Dayton Jones, Space Science Institute, Boulder
Justin Kasper, University of Michigan
Abraham Loeb, Harvard University
Raul Monsalve, University of Colorado
Jordan Mirocha, UCLA
David Rapetti, University of Colorado Boulder
Edward Wollack, NASA GSFC

Collaborators:
Michael Bicay, NASA Ames Research Center
Abhirup Datta, University of Colorado Boulder
Jonathan Pritchard, Imperial College
Eric Switzer, NASA GSFC

Graduate Students:
Bang Nhan, University of Colorado
Keith Tauscher, University of Colorado
Foregrounds and Beam Chromaticity

**Foreground Characteristics**
- Spectrally smooth
- Spatial structure
- Polarized

**Signal Characteristics**
- Spectral structure
- Spatially isotropic
- Unpolarized

Weighting by antenna beam introduces spectral structure in foreground (e.g., Bernardi et al. 2015, Mozdzen et al. 2016)
Two Year Mission Lifetime

- ~1000 hrs integration above lunar farside.
- shielded from Sun.
- 50x 125 km, equatorial orbit.

DARE probes $z=11-35$ with $v=40-120$ MHz
Chromaticity: Design Considerations

- Build antenna with low CTE material & minimize antenna thermal distortions (<10°C) with sunshade.
- Accurate modeling & measurement before launch.
- Measure beam on-orbit using frequency tones transmitted from Earth:
  - Circularly polarized, PSK modulated carriers (6) are sent from ground to DARE.
  - DARE receives signals as the spacecraft orbits above near side of the Moon to sweep beam.
  - Carrier levels are measured by DARE every 20 seconds to produce sampled beam cut.
  - A weak signal is also measured on its return trip to the Earth (Moon reflection) to estimate real-time path loss through the ionosphere.

\[
P_{echo} = \left( \frac{c^2}{64\pi^4} \right) \cdot \left( \frac{1}{v^2} \right) \cdot \left( \frac{P_t G_t^2 L_t^2 \sigma_m}{R_{t-M}^4} \right) = \text{echo power at 140-ft}
\]
Singular Value Decomposition (SVD) of Training Sets

Utility of SVD in easing requirements
• SVD is a way of writing any matrix, $M$, as a matrix product:
  $$M = U \Sigma V^T$$
  
  Training Set: $(N_{\text{channel}} \times N_{\text{curves}})$
  Ordered basis functions: $(N_{\text{channel}} \times N_{\text{channel}})$

• SVD provides the optimal basis with which to fit the curves in a given training set.

See also Switzer & Liu 2014, Paciga et al. 2013, Vedanthum et al. 2014
Training with Singular Value Decomposition (SVD)

Utility of SVD in easing requirements

• By picking out the strongest modes of variation, SVD transforms the problem of separation from an absolute one into a relative one.

Burns et al. 2017; Tauscher et al. 2017 (in prep.); Rapetti et al. 2017 (in prep.)
Separating systematics with induced polarization

**No polarization data used**

**Polarization data used**

\[
\ln L(\gamma) = -\frac{1}{2} \sum_{\alpha \in \{I,Q,U,V\}} \sum \sum \sum \sum_{\nu} \left[ \frac{S_{\alpha}(r,\phi)(\nu) - M_{\alpha}(r,\phi)(\gamma; \nu)}{\sigma_{\alpha}(r,\phi)(\nu)} \right]^2
\]

\[
M_{\alpha}^{(r,\phi)}(\gamma; \nu) = \sum_{k} f_{\alpha,k}^{(r,\phi)}(\nu) + \delta_{\alpha I} B^{(r,\phi)}(\nu) \sum_{j} g_{j}(\nu)
\]

Likelihood function
Prototype: Cosmic Twilight Polarimeter

Collaboration between NRAO & University of Colorado

Polarimetry Process to measure Foreground

1. Measure “polarization leakage” caused by $\nu$-dependence of power patterns of linearly polarized dipoles. Rotation of sky to measure modulated Stokes $Q$, $U$, $V$.
2. Harmonic decomposition of modulated $Q$, $U$ signal, scale to Stokes $I$, and subtract.

Toward a *Cosmic Dawn Mapper*

Deep Space Gateway at Earth-Moon L2 can deploy a low frequency telescope on farside via teleoperated rover.

- E-M L2 is 60,000 km above farside. Minimal station-keeping to orbit about L2.
- First uncrewed mission is 2019 & first crewed mission is ~2021.

Orion/SLS – NASA video
Deep Space Gateway

Habitat Support Vehicle
Provides power, propulsion, communications, and breathable gases for the Deep Space Gateway

Cargo/Logistics Pod
Simplified module that provides fresh supplies, crew volume, and trash disposal. Launched on SLS and ferried to Deep Space Gateway by Orion

Habitat Module
Provides systems, storage, and additional volume for 4 astronauts on 30-60 day missions

EVA Module
Allows astronauts to perform spacewalks and test advanced EVA technology

Orion Spacecraft
Brings astronauts to and from the DSTH. Provides advanced functionality to Deep Space Gateway during crew visits

Robotic Arm
Allows for berthing and re-positioning of new elements and visiting vehicles. Used during EVA to position astronauts around Deep Space Gateway
Lunar Science

- Communications Relay
- Surface Telerobotics
- Radio Astronomy
- Radiation
- Sample Return

NESS Telerobotic Deployment
Burns et al. (2013)

Lander Graphic
Courtesy JPL

Rover Image
Courtesy MDA
Telerobotic Deployment of a Lunar Radio Array

Astronaut Luca Parmitano (Italy) orbiting Earth on the ISS teleoperates the K10 rover at NASA Ames to simulate deploying a lunar farside radio telescope.


Previous Studies (circa 2009)

**DALI/ROLSS**
(Lazio et al.)
- Dipoles (1x1 m) on Kapton
- 1500 dipoles/station
- DALI: 300 stations
- ROLSS: 1 station

**LARC Cosmic Dawn Array**
(Hewitt et al.)
- Helical stances: 1.2 x 8.2 meters
- 10,000 stances
Ballpark numbers

At 10 MHz:

- 1 degree resolution requires ~2 km baselines
  - Filled aperture: 1 element / 3600 sq. m
  - Circle layout: 1 element / 6 meters
- $10^5$ square meters collecting area requires >1000 dipoles
- 1000 dipoles * 2 pol * 20 MHz bandwidth $\rightarrow$ $\sim$40 GB/s

- Power
  - Analog: 1000 dipoles * 0.1W = 200 W
  - Channelization: 2000 channels * 10W/32channels (FPGA) = 600W
  - Correlation: Currently $\sim$5 GPU servers * 500W = 2500W
  - Can likely reduce by order of magnitude with ASICs, etc.
    - LARC estimated 200W using GeoSTAR correlator
Lunar Prototype Array Trade Study

- **Literature review (Summer 2017)**
  - Previous design/trade studies (LARC, ROLSS, etc.)
  - Relevant technologies, TRLs, etc.
  - Lunar conditions
    - RFI, regolith properties, environment, dust, radiation, etc.

- **Science objective definition (Fall 2017)**
  - “Notional” full-scale science objectives
    - Exoplanet space weather, 21cm cosmic dawn, heliophysics, etc.
    - Total collecting area, observation band, angular resolution, etc.
  - Select subset of science scoped to a small prototype array

- **Trade study of design options for prototype array (Spring 2018)** - Goal to identify reference prototype design and key technology development
  - Antenna design, polarization, etc.
  - Array configuration, collecting area
  - Location on lunar surface
  - Operational model (lunar day/night, duty-cycle, etc.)
  - Processing, data rate, data volume, etc.
  - Deployment methods
  - Mass, power, cost
  - End-to-end system (communications requirements/relays, power sources/storage, etc.)
Summary and Conclusions

• The Global 21-cm Monopole signal is a powerful tool to explore the first luminous objects in the Universe and their environs at $z>10$.

• *DARE science instrument*: biconical dipole antenna, pilot-tone injection receiver, digital spectrometer, polarimeter, & SVD MCMC signal extraction pipeline.

• Prototype low frequency antennas and arrays on the lunar surface may be viable in the mid-2020’s via telerobotic deployment from NASA’s Deep Space Gateway.

• NASA-funded Trade and Science Definition studies for lunar farside arrays are underway now to prepare for deployment in the mid to late 2020’s.
We use the **BPIC (Bayesian Predictive Information Criterion)** statistic to blindly select a model with the number of SVD modes necessary to fit the data. The chosen model (red rectangle) has the minimum BPIC.