Cosmology from the Moon: Observing the Dark Ages of the Early Universe from the Farside

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The First Stars
M. Norman, B. O’Shea et al.
What is the 21-cm Global signal?

Spectral Features:

A: Dark Ages: test of standard cosmological model

B: Cosmic Dawn: First stars ignite

C: Black hole accretion begins
EDGES: Key Features

How to amplify signal by a factor of 2-3?

\[ \delta T_b \simeq 27 \bar{x}_H (1 + \delta) \left( \frac{\Omega_{b,0} h^2}{0.023} \right) \left( \frac{0.15}{\Omega_{m,0} h^2} \frac{1 + z}{10} \right)^{1/2} \left( 1 - \frac{T_R}{T_S} \right) \text{ mK} \]

1. Increase \( T_R \) via Dark Matter decay or synchrotron radiation from black holes, galaxies.
   - Feng & Holder, Ewall-Wice et al., Fraser et al., Mirocha & Furlanetto

2. Alter the cosmology.
   - McGaugh, Costa et al., Hill et al.

3. Decrease \( T_S \) via baryon-Dark Matter interactions which cools the hydrogen.
   - Barkana, Munoz & Loeb, Fialkov et al., Berlin et al., Slatyer & Wu
**DARK COSMOLOGY: INVESTIGATING DARK MATTER IN THE DARK AGES**

**OBJECTIVE 1:**
- Determine the level of (dis)agreement with the standard cosmological model caused by dark matter in the Dark Ages.

**OBJECTIVE 2:**
- Determine the level of excess cooling above the adiabatic limit for Cosmic Dawn.
- Determine when the first stars and black holes formed.

**Will the observed behavior of redshifted neutral hydrogen redefine the standard cosmological model?**

**21-cm spectrum has broad absorption troughs corresponding to the Dark Ages and Cosmic Dawn**

**DAPPER uses the 21-cm all-sky signal to observe redshifts z = 83-12, associated with the Dark Ages and the Cosmic Dawn.**

**DAPPER separates Galaxy foreground from 21-cm signal using differences in spectral shapes, spatial structure, and polarization.**

**Legend:**
- Galactic foreground
- [21-cm signal]
  - Foreground's spatial structure is irregular
  - Foreground brightness
  - Foreground is polarized, neutral hydrogen is not

**EM Spectrum**
- 10 MHz
- 60 MHz
- 120 MHz

**Time (billions of Years)**
- 0.004
- 0.5
- 1
- 9
- 13

**Big Bang**
- Cosmic Dark Ages
- Cosmic Dawn
- Reionization

**Modern Galaxies Form**
- Hubble Ultra-Deep Field
- JWST/WFIRST

**Initial Stages**
- DAPPER
- HERA
- EDGES

**First Galaxies & Black Holes**
- First Stars
Mission Overview

• DAPPER will deploy from vicinity of NASA’s Lunar Gateway & transfer to a $50 \times 125$ km low lunar orbit.

• Operates over primary bandwidth of $17-38$ MHz ($83 \geq z \geq 36$) and sparse secondary sampling from $55-107$ MHz ($25 \geq z \geq 12$).

• Low noise amplifiers & dual channel receiver to measure all 4 Stokes parameters. Based upon FIELDS instrument currently flying on Parker Solar Probe (TRL = 8).

• Projection-induced polarimetry used to independently constrain foreground.

• Baseline mission duration = 26 months.
Lunar Farside: No RFI or Ionosphere!

Wind/Waves data near the Moon
Spacecraft
- Deep Space Xplorer bus by Bradford Space Industries.
- High impulse, high ΔV.

Antennas
- Deployable, spinning, wire boom antennas arranged in 2 orthogonal, co-linear pairs.
- 3 length deployments to “tune” instrument.
**DAPPER Instrument**

- **High heritage** from Parker Solar Probe, THEMIS, Van Allen Probes.
- **Receiver gain variations:**
  - Measured with high fidelity by frequency tones.
  - Controlled by stabilizing temperatures to \( \pm 1 \, ^{\circ}\text{C} \).
- **Calibration:**
  - Pre-launch lab measurements.
  - In-flight verification.
  - Fitting receiver characteristics using pattern recognition/MCMC pipeline.
Removal of RFI using Kurtosis & Neural Network

Separate foreground from 21-cm signal using polarization & SVD

End-to-end simulation with sky + instrument systematics, signal models

DAPPER separates standard cosmology from added-cooling at >5σ
Summary

• The redshifted 21-cm Global Spectrum at $\lesssim 30$ MHz offers the prospect of probing the nature & character of Dark Matter in the Dark Ages.
• These observations need to be conducted in space, in orbit of the Moon, to eliminate Earth ionospheric, RFI, & ground effects.
• Projection-induced polarization provides an independent measure of the galactic foreground.
• We developed a method which transforms the 21-cm signal extraction task from one where absolute knowledge of system parameters is required to one of composing training sets where knowledge of the modes of variation are used.
• DAPPER will differentiate between the standard cosmology model & added cooling models at $>5\sigma$ level.

MOON GAZING

Nearly 50 years ago, NASA put a telescope on the Moon. Astronomers have been trying to return ever since

By Daniel Clery

FARSIDE array
P.I.s J. Burns & G. Hallinan