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**DARE PROJECT TEAM**

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**PARTNERSHIPS**

[Logos of University of Colorado, NASA, and Ball Aerospace]
The 21-cm Line in Cosmology

$$T_{\gamma}$$

$$T_S$$

$$T_b$$

$$z = 13$$

$$\nu = 1.4 \text{ GHz}$$

$$z = 0$$

$$\nu = 100 \text{ MHz}$$

CMB acts as back light

Neutral gas imprints signal

Redshifted signal detected

$T_b = 27 x_{\text{HI}} (1 + \delta_b) \left( \frac{T_S - T_{\gamma}}{T_S} \right) \left( \frac{1 + z}{10} \right)^{1/2} \left[ \frac{\partial_r v_r}{(1 + z) H(z)} \right]^{-1} \text{ mK}$

spin temperature set by different mechanisms:

Radiative transitions (CMB)

Collisions

Wouthysen-Field effect
DARE will focus on determining or constraining *Turning Points B, C, D*

Adapted from Pritchard & Loeb, 2010, *Phys. Rev. D*, 82, 023006
Astro 2010 identifies Cosmic Dawn as a top science objective: Searching for the First Stars, Galaxies & Black Holes

“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? Observations and calculations suggest that this phenomenon occurred when the universe was roughly half a billion years old, when light from the first stars was able to ionize the hydrogen gas in the universe from atoms into electrons and protons—a period known as the epoch of reionization… Astronomers must now search the sky for these infant galaxies and find out how they behaved and interacted with their surroundings.” => This is DARE’s science!
Lessons from EDGES

• $10^{9-10}$ dynamic range difficult because of RFI => A/D converters need high bit-depths & be highly linear. Susceptible to internal clock stability errors & digital noise.

• Multipath reflections => complex spectral interference.

• Complex environment makes transferring instrument response function from lab impossible.

• Ionosphere adds significant noise at <80 MHz.
Radio Frequency Interference in Western Australia
Lunar Advantage: No Interference!

30 MHz (z=46) to 100 MHz (z=13)

Destination: Moon

Fig. 5: Example of lunar oscillation of the Earth as observed with the upper F burst receiver. The top frame is a computer-generated dynamic spectrum; the other plots display intensity vs. time variations at frequencies where unwanted noise levels are often observed. The 60s data gaps which occur every 24h are at times when in-flight calibrations occur. The short white pulses observed every 10s at the highest frequencies during the oscillation period are due to weak interference from the Skylab Working餘器. One solution is to ensure that the moon and the burst receiver are tuned to the same frequency.
DARE’s Biggest Challenge: Foregrounds

Highest foreground (RFI) eliminated by being above lunar farside!

DARE’s Key Mission Design Features:
- Weak Stability Boundary (WSB) trajectory - requires less Δv for LOI and allows a flexible launch date
- Equatorial, 200km mean orbit altitude - long-period stability
- Low inclination orbit - maximizes Earth occultation
- Baseline Mission 3 years
- Threshold Mission 1 year
DARE’s Biggest Challenge: Foregrounds

1) Milky Way synchrotron emission + “sea” of extragalactic sources.

2) Solar system objects: Sun, Jupiter, Moon
DARE mounted on ORION
A free ride to the Moon?

Forward location

AFT location
DARE Status & Timeline

- DARE was proposed as a Explorer Mission in February, 2011.
- Mission was not accepted for Phase A study— but very high referee ratings.
- DARE Engineering prototype has been developed (NRAO and JPL).
- Instrument Verification Program includes the initial field tests in Green Bank, WV (Feb-Mar, 2012) as well as the DARE-ground experiment in Western Australia (Mar, 2012 onwards).
- Results from these experiments will be critical in re-proposing DARE for a SMEX mission in late 2013.
DARE Engineering Prototype: Components

- DARE will operate at low radio frequencies between 40-120 MHz
- Components of all three subsystems (antenna, receiver and spectrometer) are at TRL ≥ 6
- Instrument Verification Program underway to have the integrated instrument at TRL 6
Green Bank field tests

- DARE Engineering prototype was deployed at the NRAO site in Green Bank, WV.
- Recorded data for about 2 weeks.
- Initial field tests validated the performance of three stages of DARE instrument: antenna, front-end and digital spectrometer.
Initial Calibration

- \( P_{OFF} = g(T_{Load} + T_{Rcvr})(1 + n_0) \)
- \( P_{ON} = g(T_{Ant} + T_{Rcvr})(1 + n_1) \)

- Equating these two we get:
  \( T_{Ant} = \frac{P_{ON}}{P_{OFF}} (T_{Load} + T_{Rcvr}) - T_{Rcvr} \)

- To the first order of approximations:
  \( T_{sky} \sim T_{Ant} / (1 - \Gamma^2) \)

where \( \Gamma \) is the Reflection coefficient.

Calibrated spectra shows effects of:
1) Radio Frequency Interference (RFI)
2) Earth’s Ionosphere

These are two major challenges for ground based observations at these frequencies.
First Results

Galactic synchrotron spectral index $\sim 2.7$
DARE Engineering prototype was deployed on March 21, 2012 at Murchison Radio Observatory (MRO).
Strong RFI (@ 20 MHz) caused saturation of the receiver. Modified receiver has been installed.
MCMC approach to signal extraction for fiducial DARE mission

Random walk through parameter space → unbiased, random samples of the posterior probability distribution

- x Input
- + Recovered
  - 68% conf.
  - 95% conf.

Positions of turning points B, C and D

Shape of 21-cm signal

For details see Harker et al. (2012), MNRAS, 419, 1070
Modeling Earth’s Ionosphere

The ionosphere produces a contribution to the spectrum scaling as (frequency)$^{-2}$

$$T_{\text{with}} = T_{\text{without}} - T_{\text{without}}(1 - L)\left(\frac{\nu}{\nu_0}\right)^{-2} + T_{\text{electrons}}$$

**Residuals after fitting a foreground with no ionosphere to synthetic data with an ionosphere**

Blue: space-based experiment, 8 sky regions
Red: ground-based, 2 regions, with ionosphere
Nested sampling

• We have adapted the likelihood computation used in the MCMC analysis to work with the public code MultiNest, which implements the ‘Nested Sampling’ algorithm for Bayesian inference.

• Advantages
  • Flexible: works for complicated likelihood functions.
  • Allows us objectively to compare the evidence for different signal models given the data.
  • Well tested in applications in particle physics, cosmology (e.g. CMB) and lensing.

• Disadvantages
  • Not optimized for very high-dimensional parameter space.
  • Computationally intensive: has been compiled for, and is being tested on, the Janus supercomputing facility at the University of Colorado.
Future work: alternative signal models

- A wide range of values for the model parameters are allowed by current constraints.
- Alternative models (e.g. including decaying dark matter) may not be described very well by the turning points scheme.
- The nested sampling algorithm will allow us to test how well DARE can select between models with very different shapes.
- We are exploring alternative parametrizations.

Pritchard & Loeb (2010)
Dark Ages Radio Explorer (DARE)

- DARE is designed to address:
  - When did the First Stars ignite?
  - When did the first accreting Black Holes turn on?
  - When did Reionization begin?

- DARE will accomplish this by:
  - Constructing first sky-averaged spectrum of redshifted 21-cm signal at 11<z<35.
  - Flying spacecraft in lunar orbit & collecting data above lunar farside -- only proven radio-quiet zone in inner solar system.
  - Using biconical dipole antennas with smooth response function & Markov Chain Monte Carlo method to recover spectral *turning points* in the presence of bright foregrounds.
  - Using high heritage spacecraft bus (WISE) & technologies/techniques from EDGES.

http://lunar.colorado.edu/dare/