Detecting the First Galaxies with the Global 21-cm Signal: The Dark Ages Radio Explorer

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The 21-cm Global Signal Reveals the Birth & Characteristics of the First Stars & Galaxies

DARE operates at $\nu = 40$-120 MHz, probing redshifts $z = 11$-35

--- uncertainties in 1st star models
--- uncertainties in 1st black hole models

Range of Model Parameters for 1\textsuperscript{st} Stars & Galaxies

courtesy Jordan Mirocha
Observational Approaches for Detection of Global 21-cm Monopole

Single Antenna Radiometers

- EDGES (Bowman & Rogers)
- SARAS (Patra et al.)
- LEDA (Greenhill, Bernardi et al.)
- SCI-HI (Peterson, Voytek et al.)
- BIGHORNS (Sokolowski et al.)
- DARE (Burns et al.)

Challenges include systematics arising from stability issues, accurate calibration, polarization leakage, foregrounds.

Small, Compact Interferometric Arrays

- Vadantham et al.
- Mahesh et al.
- Presley, Parsons & Liu
- Subrahmanyan, Singh et al.

Challenges include cross-talk among antenna elements, mode-coupling of foreground continuum sources into spectral confusion, sensitivity.
Foregrounds: Major Challenge

- **Earth’s Ionosphere** (e.g., Vedantham et al. 2014; Datta et al. 2016; Rogers et al. 2015; Sokolowski et al. 2015)
  - Refraction, absorption, & emission
  - Spatial & temporal variations related to forcing action by solar UV & X-rays => 1/f or flicker noise acts as another systematic or bias.
  - Effects scale as $v^{-2}$ so they get much worse quickly below ~100 MHz.

- **Radio Frequency Interference (RFI)**
  - RFI particularly problematic for FM band (88-110 MHz).
  - Reflection off the Moon, space debris, aircraft, & ionized meteor trails are an issue everywhere on Earth (e.g., Tingay et al. 2013; Vedantham et al. 2013).
  - Even in LEO ($10^8$ K) or lunar nearside ($10^6$ K), RFI brightness $T_B$ is high.

- **Galactic/Extragalactic**
  - Mainly synchrotron with expected smooth spectrum ($\sim 3^{\text{rd}}$ order log polynomial, $\log T_R = \sum_{i=0}^{N_{\text{poly}}} a_i \log \left( \frac{v}{v_0} \right)^i$, although it is corrupted by antenna beam; e.g., Bernardi et al. 2015).
  - EDGES finds spectral structure at levels <8 mK in foreground at 100-200 MHz.

- **Other Foregrounds** - lunar thermal emission & reflections; Jupiter; Recombination lines.
Extraterrestrial Foregrounds

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

2) Solar system objects: Sun, Jupiter, Moon.

=>Must employ advanced statistical techniques to simultaneously fit signal, foregrounds, & instrument parameters.
Detecting the strongest spectral feature in the presence of the Galactic foreground

- Haslam quiet sky region, constant spectral index.
- Convolved with $\nu$-dependent Gaussian beam.
- Ares 21-cm Global Signal model, 3 Turning Points.
- 1000 hrs integration with DARE sensitivity.
- Polynomial fit removed from foreground.

**Instrument Requirement:** Minimal Chromatic beam effects

Keith Tauscher & J. Burns
Signal Extraction using MCMC

End-to-end extraction results using EMCEE for DARE instrument parameters: 1000 hr, 4 sky regions.

This technique captures degeneracies & covariances between parameters, including those related to signal, foregrounds, & the instrument. Extensive heritage from CMB observations by WMAP & Planck.

For details, see Harker, Mirocha, Burns, & Pritchard (2016), MNRAS, 455, 3829.
Characterizing the First Stars & Galaxies

Using an MCMC statistical framework, the Galactic foreground is fit along with the physical parameters of the first luminous objects yielding these confidence intervals on physical parameters. Modeling assumes DARE instrument sensitivity.

Global Experiments have the potential to bound the properties (e.g., mass, spectra) of the first generation of stars, black holes, & galaxies for the first time (0.1-0.2 dex).

Science Instrument

Antenna: Dual, deployable bicones to accommodate launch volume
- Mast deploys bicones above S/C deck
- Bicones deploy to achieve length
- Jib Radials deploy to form ground plane

Receiver: Pseudo-correlation Architecture + Reflectometer
- Heritage from WMAP, Planck, Microwave Limb Sounder on UARS.
- Thermally controlled front-end receiver electronics enclosure

Spectrometer
- Achieves $10^6$ dynamic range
- Uses space-qualified FPGAs.
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**: broad-band dipole antenna, pseudo-correlation receiver, digital spectrometer, radial ground screen.

- **MCMC fits set meaningful constraints on**: Ly-α, ionizing, & X-ray backgrounds along with minimum virial temperatures of halos.

- DARE will be proposed in response to the NASA Explorer AO in late 2016.
Supplemental Slides

DARK AGES RADIO EXPLORER

DARE
The 21-cm Line in Cosmology

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

- **Brightness temperature**: \( P = kT_b \Delta \nu \)
- **Neutral fraction**
- **Baryon density**
- **Spin temperature**
- **Peculiar velocities**

CMB acts as back light

Neutral gas imprints signal

\( z = 13 \)
\( \nu = 1.4 \text{ GHz} \)

Redshifted signal detected

\( z = 0 \)
\( \nu = 100 \text{ MHz} \)

Spin temperature set by different mechanisms:
- Radiative transitions (CMB)
- Collisions
- Wouthysen-Field effect

Courtesy of J. Pritchard
Parameterizing the 21-cm Model

- Previous studies parameterized signal from just the 3 Turning Points.
- A more physically-motivated approach to model the Ly-α, IGM thermal, & ionization history is a *tanh* model:

\[
A(z) = \frac{A_{\text{ref}}}{2} \left\{ 1 + \tanh\left[ \frac{(z_0 - z)/\Delta z}{2} \right] \right\}
\]

- Significantly improves extraction of 21-cm signal from Foregrounds, reducing biases.