Design & Science of the Mileura Wide-field Array

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Overview

• MWA Overview
• Introduce EOR Science
• Design of the MWA-LFD
  • EOR Analysis
  • Radio Transient Search
Mileura Station

Very radio quiet
Mileura Wide-field Array

Low Frequency Demonstrator (MWA-LFD) 80–300 MHz

New Technology Demonstrator (MWA-NTD) 0.8–1.6 GHz
Combined Management, Development, & Infrastructure
The Epoch of Reionization
MIT EOR Workshop

Ger de Bruyn, Jacqueline Hewitt, Matias Zaldarriaga, Colin Lonsdale, Avi Loeb, Steven Furlanetto, Miguel Morales, Peng Oh, Frank Briggs, Paul Shapiro, Xiaohui Fan, Ron Ekers, Xuelei Chen, Jeff Peterson, Zoltan Haiman, Saleem Zaroubi, Judd Bowman, Stuart Wyithe, Renyue Cen, Rachel Webster, Mario Santos, Namir Kassim, Tzu-Ching Chang, David Barnes, Steve Nadis, Ue-Li Pen, Andrei Mesinger, Lincoln Greenhill, Mark Dijkstra, Matt McQuinn
How did we get from smooth CMB to clumpy galaxies?
Point Source Foreground

- Bright sources removed carefully
- Faint sources can be removed using smooth spectral characteristics (Briggs & de Bruyn, in prep.; Zaldarriaga et al. 2004)
Galaxy & Radio Recombination Lines

Use multi-frequency maps to subtract (like in CMB observations)
Ionosphere & Polarization

Lonsdale (2004)

325 MHz polarized flux, 6° x 6°, 4’ beam, 5 K peaks (de Bruyn)
Theory Questions

• Uncertainty in:
  • Global HI fraction as a function of redshift
  • Spin temperature & Lyman-\(\alpha\) background
  • Reionization dynamics

• Lots of feedback for star formation, heating, etc.

• Work on degeneracies and understanding interactions

• Work on signatures for data interpretation & other science with 21 cm tomography
21 cm Signatures

- Global reionization step
- Statistical properties – power spectrum & non-Gaussian statistics
- Quasar bubbles – around known high redshift quasars & fossil HII regions
- 21 cm forest
- Imaging
## Science – Experiment Matrix

<table>
<thead>
<tr>
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<th>ATNF Global</th>
<th>PAST</th>
<th>MWA-LFD</th>
<th>LOFAR</th>
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<tbody>
<tr>
<td>Global step</td>
<td>✓</td>
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<td>Statistical</td>
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<tr>
<td>Quasar HII bubbles</td>
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<td>21 cm forest</td>
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<td>Imaging</td>
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<td>Initial Operation</td>
<td>2005</td>
<td>2006</td>
<td>2007</td>
<td>2007</td>
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Summary of Workshop

- Huge science return, major experimental campaign
- No show stoppers
- Lots of work to do
  - Theory: understanding signatures, how to interpret the data
  - Analysis: source foregrounds, statistics
  - Experiment: building telescopes, understanding calibration and instrumental foregrounds
Mileura Wide-field Array
Low Frequency Demonstrator
(MWA-LFD)

Collaborating institutions:
• MIT & Haystack Observatory
• Harvard–Smithsonian Center for Astrophysics
• Australian University Consortium (Melbourne, ANU, etc.)
• Australia Telescope National Facility (ATNF)
• Government of Western Australia
Goals of MWA-LFD

- Technology of wide-field observations
- Wide field science:
  - Epoch of Reionization
  - Heliospheric Science — FR & IPS
  - Radio Transients
Antenna Design
Characteristics of the Array

- 500 16-element antennas in a compact 1.5 km array
- Wide 80–300 MHz frequency range
- Digital receiver & filter chain, 32 MHz at 8 Khz resolution
- Full cross-correlation of all 500 antennas, 20–30° field of view
Keep It Simple

• Straightforward calibration (no long baselines or frequencies below 80 MHz)

• Single mode systems (correlator hardwired to 8 kHz & 1/2 sec resolution, etc.)

• Campaign scheduling, science performed by dedicated collaborations
EOR Science Collaboration

MIT: Jacqueline Hewitt, Miguel Morales, Colin Lonsdale
Melbourne: Rachel Webster, Stuart Wyithe, David Barnes
CfA: Matias Zaldarriaga, Avi Loeb, Lincoln Greenhill, Lars Hernquist
Other Institutions: Steve Furlanetto (Caltech), Chris Carilli (NRAO), Frank Briggs (ANU)
Statistical EOR Detection

- Image Cube
- FT Sky Coordinates
- Visibilities
- FT Frequency
- Fourier Representation
Spherical Symmetry

Symmetry for Residual Foreground Removal

Simulated signal cube

Bowman & Morales, in prep.
Differentiating Models

Predictions for 21 cm Tomography

Evolution of angular power spectrum:
- Dotted: $z=18$, $\Omega_H=0.96$
- Short-dashed: $z=15$, $\Omega_H=0.81$
- Long-dashed: $z=13$, $\Omega_H=0.52$
- Solid: $z=12$, $\Omega_H=0.26$

Many open questions:
- How accurate is the model?
- How do recombinations change the picture?
- What role does small-scale structure play?
- How do evolving sources modify the bubbles?
- How much does anisotropy matter?

How Did Reionization Happen?

The $\delta T_b$ field is non-gaussian because of HII regions. Higher-order statistics are crucial.

- Dotted: uniform
- Dashed: voids ionized first
- Solid: overdense regions ionized first

FZH (2004a)

FZH (2004b)
Power Spectrum

MWA-LFD, 100 hours, z = 10
Foregrounds

- Faint Point Sources
- Smooth Galactic Emission
- Galactic Radio Recombination Lines
- Instrumental Polarization
- RFI
- Others!

6 x 6 °
Polarised flux
~ 5 K peak
on 4’ scales
EOR Collaboration Tasks

Software & hardware to:

• Calibrate visibility cubes and integrate to ~10 min.

• Store in 100 terabyte database with detailed observation characteristics

• Integrate to form long integration visibility cube with best data at Mileura
MWA-LFD & EOR

- Premier EOR instrument
- Strict attention to systematic errors:
  - Ionospheric & instrumental calibration
  - Point Spread Function
  - Spectral Contamination

http://web.haystack.mit.edu/MWA/mdemonstrator.html
Radio Transient Collaboration

MIT: Miguel Morales, Jacqueline Hewitt, Roger Cappallo, Justin Kasper

Naval Research Laboratory: Joseph Lazio, Namir Kassim
Possible Sources

- Radio Supernovae
- Gamma Ray Bursts
- Solar & Stellar radio bursts
- Planetary radio bursts
- AGN variability
- Microquasars
- Microlensing
- Magnetars
- LIGO & LISA Events
- ???

*Prompt & Sustained*
ASM Transient Search

- 5 dimensional search over position, start time, duration, & dispersion measure

- Expected statistical distribution must be well determined (trials, systematics)

- Pixel-by-pixel statistics must be understood
~2 Billion Visibility Measurements Every 1/2 second, Filtered for Blatant RFI

Ionosphere
Calibration
Containing Refraction and Magnification Across the FOV

Determine Expected Visibilities from Global Model and Ionosphere Map

Form Expected Variance Map

Form De-dispersed Visibility Grids, Separate Grid for Each Trial Dispersion

Filter for Moderate RFI

Subtract Sources from Visibility-Frequency-Time Data

Form Gridded Visibility-Frequency-Time Data for De-dispersion and RFI Identification

Expected Source Contribution

Visibility Processing

Raw Visibilities

Calibration Solution

ASM Analysis Diagram
Add Intensity Maps

Locate Sources and Determine Probability of Being Produced by Background Fluctuations

ID Interesting Sources

Notification and Triggering for Identified Sources

Pass Composite Source Map to Next Timescale Search

For ~1,000 Sources of Interest, Archive Flux for Monitoring Purposes

Database All Significant Source Variations

Determine Expected Visibilities from Global Model and Ionosphere Map

Form Expected Variance Map

Transient Identification
Repeated for Each Timescale and Trial Dispersion Measure

Use Ionospheric Calibration to Form Calibrated 1/2 second Residual and Variance Maps for Each Dispersion

Filter for Moderate RFI

For ~1,000 Sources of Interest, Archive Flux for Monitoring Purposes

Add Intensity Maps

Locate Sources and Determine Probability of Being Produced by Background Fluctuations

ID Interesting Sources

Notification and Triggering for Identified Sources

Pass Composite Source Map to Next Timescale Search

For ~1,000 Sources of Interest, Archive Flux for Monitoring Purposes

Database All Significant Source Variations

Determine Expected Visibilities from Global Model and Ionosphere Map

Form Expected Variance Map
MWA-LFD & Radio Transients

- Perform comprehensive survey for transients from 80-300 MHz
  - ~6 orders of magnitude more sensitive than any previous transient survey in the band (~0.2 Jy per sqrt sec)
- Develop software & expertise for transient sources on other wide field observatories
- Prototyping is underway with GASE experiment
Conclusion

*MWA will:*

- Develop technology & software for very wide field observations
- Perform best of generation EOR observations
- Demonstrate Faraday rotation monitoring of heliosphere & applications to space weather
- Create deep radio transient survey
- Other science: sky survey with FR, pulsars, IPS, other collaborations