21cm Observations of the Epoch of Reionization

Jacqueline N. Hewitt
for the Mileura Widefield Array collaboration
Epoch of (Reheating and) Reionization
HI Fluctuations

Reheating

z=8.5

Size of box is 20/h comoving Mpc

Resolution = 1'
Bandwidth = 1 MHz
Frequency = 150 MHz

rms is about 10 mK

$z = 12.1, 11.1, 10.4, 9.8, 9.2, 8.7, 8.3, 7.9, 7.6$

Bandwidth = 100 kHz  
Box size = $10/h$  
comoving Mpc

Fluctuations are about 10 mK

Furlanetto, Sokasian, Hernquist 2004
Power Spectrum

Reheating

The graph shows the squared visibility (in arbitrary units) as a function of baseline length (in meters) for different values of $z=10, 20, 30$. The curves indicate the decay of visibility with increasing baseline length.
Furlanetto, Zaldarriaga & Hernquist 2004
Ionization fraction $x = 0.96, 0.8, 0.5, 0.26$

Many bubbles are large because of clustering
Fundamental Problem:
Low frequency radio astronomy is hard

- Sky noise
- Confusion
- RFI
- Aperture synthesis flat sky approximation fails
- Ionospheric fluctuations
- Field of view larger than isoplanatic patch
408 MHz Radio Map of the Sky – 1982

Resolution 0.85 degrees

Haslam et al. 1982 A&A Supp 47 1
Spectral and spatial smoothness of the low frequency sky in deep (48h) image around 325 MHz. Lowest contour 1 mJy/beam = 4 K. Noise level 0.3 mJy (confusion limited).

Westerbork map
325 MHz
1.5 X 1.5 degrees
Lowest contour = 4K
Polarimetry II

by Bryan Gaensler
Marijke Havercorn

Polarization from Cygnus (Uyaniker et al 2003)
Galactic hydrogen/carbon recombination lines:

- In Galactic plane: ~100 - 500 mK (at 325 MHz, e.g. Roshi et al, 2001)
- Out of plane: probably less than 50 mK

Fluctuations on 3-10’ scale probably an order of magnitude smaller still
Lines around 150 MHz probably weaker

NB: IF recomb lines are detected they will be helpful for fidelity checks.
Lines can easily be excised:
(~20 kHz / ~1 MHz or ~2% of spectrum)

de Bruyn 2005
Briggs & de Bruyn, unpublished

Average Flux Density per pixel

RMS fluctuation per plane in cube
- no subtraction
- linear
- quadratic

After subtraction of continuum in each pixel
Radio Frequency Interference

Background Radiation at 131.0 MHz (mV/m)

FORTES satellite
Wide-field Imaging

Unfaceted

Faceted
Another approach: Measure grid of bright sources on short time scales; fit for phase variation across field

"Perley et al., "The 4-Meter All-Sky Survey"
Ionospheric Fluctuations

Electrical path length proportional to wavelength squared!

Ionospheric phase fluctuations are usually smooth in frequency and time

15 km VLA baseline

Thick line: 74 MHz phase
Thin line: 330 MHz phase times ratio of frequencies

Kassim et al. 1993  AJ 106 2218
“Field Calibration”

Fig. 1.— A comparison of traditional, angle-invariant self-calibration (left), and Zernike-based, angle-dependent field calibration (right). Both images show the positions of sources stronger than a set peak flux cutoff in maps made from the same dataset. The source circled in the upper right of each panel is a bright 3C source which dominates the field. Traditional self-calibration applies only a single phase correction and cannot correct the ionospheric phase fluctuations far from the 3C source. These uncorrected fluctuations appear as time variable refractive errors in the map which, when averaged, smear out the distant sources, causing them to effectively disappear. By contrast, the position dependent field calibration, as implemented by VLAFM, allows for varying phase corrections across the field of view. With the refractive errors corrected, source brightness is preserved, and the source distribution across the field is more uniform.

Perley et al., “The 4-Meter All-Sky Survey”
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Radio Frequency Interference

FORTES satellite
Antenna wire structure
- 0.52 mm diameter copper wire
- 2-arm log-spiral winding on the support structure
- Can remove and replace the wires in the field
- with different pitch
- 2-arm => 4-arm

Goal: frequency independent beam over one octave of bandwidth

Subrahmanyan, Ekers, Chippendale 2005
Initial tests at Sydney

Subrahmanyan, Ekers, Chippendale 2005
Upgrade path

Absorber: vertical wall of ferrite tiles.

FI antenna:

Circulator

Noise injection

Tunable high pass filter
Low noise amplifier

Amplifiers/filters/attenuators
Tunable notch filter

Total power detector
Cross correlation spectrometer

Subrahmanyan, Ekers, Chippendale 2005
# EOR Experiments

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What does the VLA EOR look like?
- Mating of dipole feed & mechanical antenna.
- Similar to Westerbork.
- But larger, 2D array.
- Contrast to MWA-LFD, LOFAR, & PAST purpose-built facilities.

Traditional VLA receivers
\[ \lambda 20 \text{ cm-} \lambda 7\text{mm} \]
\( \lambda 92 \text{ cm} \)

\( \lambda 153 \text{ cm} \)

\( \lambda 400 \text{ cm} \)

(removable)
RFI is a major problem
Internal / External RFI

3C295, antenna 6, 05May18 - KNMD off

Uncalibrated Amplitude

Frequency (MHz)
# EOR Experiments

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LOFAR Site
LOFAR Initial Test Station
A 4-tile test setup being erected near the WSRT (June 2005)

WHAT = Westerbork Highband Antenna Teststation

First results, including cross-correlation with WSRT, expected mid-July

de Bruyn 2005
a possible `station' of 101 `4x4 tiles'

Size
in $\lambda$

de Bruyn 2005
This map was produced using 86 snapshots with 6.7s of integration and 9.7kHz channels. First RFI free channels between 29.5 and 30.5 MHz were selected using a median filter. The selected channels were calibrated on the four strongest 3C sources (Cas A, Cyg A, Tau A, Vir A). After the calibration a first map was made by a flux conserving projection from the (t, m) grid of the individual snapshots to the (α, δ) grid of the all sky image. This map was dominated by the averaged out sidelobes of Cas A and Cyg A. Therefore these two sources were cleaned from the image resulting in this map.
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PAST

Peterson, Pen, Wu
Status as of May 2005: 20 127-antenna pods assembled; 12 collecting data

New: two correlators on site
## EOR Experiments

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Mileura Widefield Array
MWA Antenna Element
HBA LNA (single polarization channel)
Prototype HBA 4-channel beamformer
Figure 1. Assembly work on tile 2.

Figure 2. Close up view of the ground screen and dipole antennas of tile 2.

The beamformer can be seen on the ground screen and dipole antennas of tile 2.

Figure 3. The completed tile 2.

Figure 4. Solar panels, which charge a battery.

Figure 5. The full ED2 setup. The two tiles, 145 meters apart, are just visible at the edge of the bushes, with the equipment caravan and vehicles in the middle.
Sky spectrum at Mileura Station
Sky spectrum at LOFAR site
Figure 7. Sky image sequence at 200 MHz. These plots show the Mileura sky in the same way as figure 6, but in this case 110 pointings per image were used. The images cover a LST range of about 10 hours, sampled over 2 days, and the spacing between frames is not uniform. Also, frames 10 and 12 have some missing data. At 200 MHz, the tile has a beamwidth of ~18 degrees, and the expected grating lobes ~100 degrees apart are clearly apparent in the “doubling” of features at high zenith angles. The color range, as in figure 6,
Figure 9. Interferometry data for three discrete sources. The axes are frequency (vertical) covering ~4.5 MHz, and time (horizontal) covering 1 hour. The colors represent the value of the real part of the interferometric complex visibility, and the stripes are a manifestation of phase ramps in time and frequency due to delay and fringe rate in the interferometer. Slanting lines (phase changes with frequency) indicate a delay between the antennas on the baseline, while the horizontal spacing of the stripes measures the phase rate from the changing baseline geometry due to earth rotation. The three sources from left to right are Centaurus A at 80 MHz, Taurus A (the Crab) at 150 MHz, and Virgo A at 150 MHz. There is an intermittent narrowband interferer at just above 150 MHz which has been edited out of the Taurus and Virgo data (white vertical lines). The frequency and time resolutions are 144 kHz and 70 seconds respectively, and the observing duty cycle within each time cell is 30%. The data indicate nominal performance of the equipment. The tile 1 to tile 2 baseline (145 meters) is too short to show pronounced ionospheric effects.
Fornax A

N=3

N=many
Measuring the power spectrum:

We measure the visibility in many frequency channels:

\[ V(u, v, \Delta f) \]

A Fourier transform along the frequency axis gives us \( \Delta \tilde{I}(u, v, \eta) \):

\[ \Delta \tilde{I}(u, v, \eta) = \int V(u, v, \eta)e^{-2\pi i \Delta f \eta} d(\Delta f) \]
Measuring the power spectrum (con.):

The specific intensity relative to the cosmic radio background is due to fluctuations in the neutral hydrogen density:

\[
\Delta I(r^*) = (2.9 \, mK)h^{-1}(1 + z)^2 \frac{(T_s - T_{CMB})}{E(z)} \frac{\rho_{HI} - <\rho_{rmHI}>}{<\rho_{HI}>}
\]

Therefore, by measuring the expectation value of the square of the visibilities we measure the neutral hydrogen power spectrum:

\[
<|\Delta \tilde{I}(u_1, v_1, \eta_1)|^2> = \int P_{HI}(u, v, \eta)|W(u_1-u, v_1-v, \eta_1-\eta)|^2dudv,
\]

where \(W(\theta_x, \theta_y, \eta)\) is the weighting function of the observations (field of view and bandwidth), and \(W(u, v, \eta)\) is its Fourier transform.

Morales & Hewitt 2004
Fig. 4.—Same as Figure 3, but computed for observations at four redshifts. From left to right, the redshifts are $z = 6, 8, 10,$ and 12. Note that the vertical scales are different for each of the upper plots. The small peaks in uncertainty at $k \approx 0.5$ for $z = 10$ and 12 correspond to the increase in uncertainty due to thermal noise at length scales sampled by the largest baselines (see Figure 2).

500 tiles; 8 MHz bandwidth; 360 hours integration; no foregrounds

Bowman, Morales & Hewitt 2005
Comparison of arrays for power spectrum measurement

Thermal noise plus sample variance

MWA 500 is blue
LOFAR is red
SKA is black
Signal is green

McQuinn et al 2005
Fig. 5. — Same as Figure 4, Column 2 for redshift $z = 8$, but the data points show a simulated realization of the measured power spectrum. The error bars are the $1 - \sigma$ uncertainties calculated from the thermal noise. The dashed lines are different values of the ionization fraction in the Furlanetto et al. (2004a,b) models and are, from top to bottom, $x_i = 0.51$, 0.0 (solid), 0.43, 0.38, 0.25, and 0.13. Note that the amplitude of the power spectrum for the fully neutral IGM is within those of the other ionization fractions. In general, the amplitudes of the model power spectra drop rapidly between $x_i = 0.0$ and 0.13, and then slowly increase with ionization fraction as large bubbles increase the contrast.
In your dreams: power spectrum without gastrophysics

MWA 5000

z=8 to 10

No reionization

Bowman, Morales, Hewitt 2005
68, 95% C.I.
Box size is WMAP 2-sigma
What does the VLAEOR ext. look like?

- Mating of dipole feed & mechanical antenna.
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