History of IGM

C. Carilli (NRAO) NNIW Dec 04

Epoch of Reionization (EoR)

- bench-mark in cosmic structure formation indicating the first luminous structures
The Gunn Peterson Effect

Fast reionization at $z=6.3$ => opaque at $\lambda_{\text{obs}}<0.9\mu m$

$f(\text{HI}) > 0.001$ at $z = 6.3$

Fan et al 2003
$Z_{\text{host}}(\text{CO}) = 6.419; \quad Z_{\text{gp}} = 6.32 \Rightarrow \text{photons leaking } 6.32 < z < 6.419$

‘time bounded’ Stromgren sphere: $R = 4.7 \text{ Mpc} \Rightarrow$

- $t_{QSO} = 1e5 \ R^3 \ f(\text{HI}) = 1e7 \text{yrs}$ for $f(\text{HI}) = 1$ or
- $f(\text{HI}) > 0.1$ at $z > 6.2$ for $t_{QSO} = t_{\text{fid}} > 1e6 \text{ yrs}$
Complex reionization \( z=6.3 \) to 17?

- GP \( \Rightarrow \) fairly fast at \( z=6.2 \)
- CSS \( \Rightarrow \) very fast at \( z=6.2 \)?
- WMAP \( \Rightarrow \) complex to \( z=17 \)?

See also Cosmic Stromgren Surfaces (Mesinger & Haiman 04), but cf. Ly \( \gamma \), Oh & Furlanetto 05

\[
\begin{array}{c}
\text{CSS} \\
6.4, >0.1
\end{array}
\]

\[
\begin{array}{c}
\text{GP} \\
6.2, >1e-3
\end{array}
\]

\[
\begin{array}{c}
\text{WMAP} \\
15, < 0.5
\end{array}
\]
HI 21cm Tomography of IGM at 100 – 200 MHz
Zaldarriaga + 2003

- $\Delta T_B(2') = 10'$ s mK
- SKA rms(100hr) = 4 mK
- LOFAR rms (1000hr) = 80 mK
VLA-VHF: 180 – 200 MHz prime focus dipole (CfA/NRAO)

- Leverage: existing telescopes, IF, correlator, operations
- $110K D+D/construction (CfA)
- Labor (CfA/NRAO)

Table 1. Personnel & Responsibilities

<table>
<thead>
<tr>
<th>Personnel</th>
<th>Inst.</th>
<th>Background</th>
<th>Responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>L. Greenhill</td>
<td>SAO</td>
<td>sei</td>
<td>Project scientist and manager; data analysis</td>
</tr>
<tr>
<td>R. Blundell</td>
<td>SAO</td>
<td>sei/eng</td>
<td>Lead for SAO receiver lab activities</td>
</tr>
<tr>
<td>E. Tong</td>
<td>SAO</td>
<td>eng</td>
<td>Antennas and electronics design</td>
</tr>
<tr>
<td>R. Kimberk</td>
<td>SAO</td>
<td>eng</td>
<td>Construction and lab testing; deployment</td>
</tr>
<tr>
<td>S. Leiker</td>
<td>SAO</td>
<td>eng</td>
<td>Construction and lab testing; deployment</td>
</tr>
<tr>
<td>C. Carilli</td>
<td>NRAO</td>
<td>sei</td>
<td>Prototype testing; commissioning calibration and measurement; data analysis</td>
</tr>
<tr>
<td>R. Perley</td>
<td>NRAO</td>
<td>sei/eng</td>
<td>Prototype testing; commissioning calibration and measurement; data analysis</td>
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<tr>
<td>A. Loeb</td>
<td>Harvard</td>
<td>sei</td>
<td>Theory and modelling</td>
</tr>
<tr>
<td>M. Zaldarriaga</td>
<td>Harvard</td>
<td>sei</td>
<td>Theory and modelling</td>
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<tr>
<td>S. Furlanetto</td>
<td>CalTech</td>
<td>sei</td>
<td>Theory and modelling</td>
</tr>
</tbody>
</table>
Main Experiment: Cosmic Stromgren spheres around $z=6$ to 6.5 SDSS QSOs (Wyithe & Loeb 2004)

- VLA spectral/spatial resolution well matched to expected signal: 7’, 1000 km/s
- Set first hard limits on $f(HI)$ at end of cosmic reionization ($f(HI) < 0.3$)
- Easily rule-out cold IGM ($T_s < T_{ cmb}$): signal = 360 mK
System/Site characteristics

First sidelobe = 15db

Table 1. VLA Low Frequency Systems

<table>
<thead>
<tr>
<th>Band</th>
<th>Passband</th>
<th>$A_s$</th>
<th>$T_{\text{ra}}$</th>
<th>$T_{\text{sky}}$</th>
<th>D/λ</th>
<th>RMS(10min)</th>
<th>Δ/λ</th>
<th>Focus loss</th>
<th>FoV</th>
<th>(FoV/sealed rms)$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>71</td>
<td>73-74.5</td>
<td>0.15</td>
<td>$\cdots$</td>
<td>$10^2$</td>
<td>6</td>
<td>150</td>
<td>0.10</td>
<td>0.01</td>
<td>9.3</td>
<td>0.004</td>
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<tr>
<td>VHF</td>
<td>178-202</td>
<td>0.50</td>
<td>60*</td>
<td>100</td>
<td>16</td>
<td>2</td>
<td>0.27</td>
<td>0.06</td>
<td>3.5</td>
<td>0.43</td>
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<tr>
<td>320</td>
<td>305-337</td>
<td>0.40</td>
<td>100*</td>
<td>25</td>
<td>27</td>
<td>1.4</td>
<td>0.43</td>
<td>0.24</td>
<td>2.1</td>
<td>0.11</td>
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<tr>
<td>1400</td>
<td>1240-1700</td>
<td>0.55</td>
<td>30</td>
<td>3</td>
<td>125</td>
<td>0.06</td>
<td>$\cdots$</td>
<td>$\cdots$</td>
<td>0.5</td>
<td>0.25</td>
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0.5db loss (12%) at 327 due VHF
Challenges and ‘mitigation’: VLA-VHF CSS

- Ionospheric phase errors – Freq^-2; 4deg FoV; 1km B_{max}
- Sky temp = 100 (ν/200 MHz)^{-2.6} K
- Confusion (in-beam) – spectral measurement (eg. Morales & Hewitt 2004); mJy point source removal w. A array; precise position and redshift
- Wide field problems – polarization, sidelobes, bandpass – all chromatic?
- RFI – “interferometric excision” (but D array); consistently ‘clean’ times in monitor plots (but very insensitive measure)?
- Effect on P/L?
**Timeline:** Funding proposal accepted SAO Aug 04

- Observing proposal NRAO Sept 04
- P/VHF feed tests SAO Dec 04
- M+T doc. for NRAO Dec 04
- Construct 10:1 scale model SAO Dec 04
- Construct/deliver prototype SAO Jan 05
- Single dish tests: RFI, impact L/P, T_{sys}, beam, eff… VLA Jan-Feb 05
- Interferometric tests 4 ants Mar-Apr 05
- Final design choice (fixed/deployable) Apr 05
- Full const/installation May – Aug 05
- First exp (150hr) D array Q4 05
- Large proposal: D array, Q1 07
Probing Cosmic Reionization with the VLA

- High freq: Study physics of the first luminous sources – mol gas + star form/AGN
- VHF: study process of reionization via CSS → set first hard constraints on f(HI) (<0.3) during the EoR
- Legacy: free new Rx band, potentially ‘band of choice’ at low frequencies