HI Intensity Mapping for large-scale structure studies

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Science goal: Baryon Acoustic Oscillations (BAO)

- Sound waves in the photon-baryon plasma in the early universe propagate from density perturbations;
- Waves freeze out when universe transited from radiation to matter domination (recombination);
- Thus they have a characteristic scale of $10^9 \, h^{-1} \text{Mpc} \approx 150 \, \text{Mpc}$, corresponding to the sound horizon at recombination at $z \approx 1100$. 

Courtesy of D. Eisenstein
The oscillation peaks and troughs on the CMB power spectrum are obvious.
The oscillation features on the large-scale matter power spectrum have also been measured.

courtesy of M. Blanton

SDSS III BOSS

Anderson+12
BAO detected in multiple surveys

107 $h^{-1}$ Mpc = 148 Mpc

$h = 0.72$
BAO: great tool for precision cosmology

- CMB-like acoustic oscillations: imprinted standard ruler, 150 Mpc.
- Present in current matter distribution that can be traced by galaxies and HI
- Efforts: e.g., WiggleZ, BOSS, PFS, HETDEX, DESI, Euclid, LSST, WFIRST
CAN WE USE **HI INTENSITY MAPPING**?

as a tracer of Large-scale Structure

• Different bias compared to other optical tracers
  • good for e.g. RSD measurements (Buetler+12)
  • useful for multi-tracer technique to get rid of cosmic variance (Seljack & McDonald 09)

• Different systematics

• In principle economical and efficient
Intensity Mapping

- Due to small emissivity, HI in emission is difficult to detect.
- Previously, HI direct detection at z~0.2 (Verheijen et al. 2010), stacking at z~0.37 (Lah et al. 2007); both on galaxy scales.

WiggleZ
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Intensity Mapping


- instead of HI associated with galaxies, interested in HI associated with large-scale structure
- measure the collective HI emission from a large region, more massive and luminous, without spatially resolving down to galaxy scales.

- Measurement of spatially diffused spectral line, in the confusion-limited regime, but redshift information is retained.
- Brightness temperature fluctuations on the sky: just like CMB temperature field, but in 3D
- Low-angular resolution redshift surveys: LSS science, economical
HI Intensity Mapping Experiment: economical and competitive to DETF stage III experiment (BOSS, DES, PFS) for dark energy constraints with 10,000 m² of collecting area.

FIG. 3: The observable parameter space in redshift and in scale (k) for BAO. The shaded regions are observationally inaccessible (see text). The horizontal lines indicate the scale of the first three BAO wiggles, and the dashed lines show contours of constant spherical harmonic order ℓ.

Chang et al. 2008
21cm Intensity Mapping current/future telescopes

CHIME/Tian-Lai/CRT/BAO Radio

GBT-HIM multi-beam

BAOBAB

FFT/OMNISCOPE Telescope

BINGO

SKA-low and SKA-mid Telescope
21cm Intensity Mapping

Observational Challenges:

• RFI, Galactic Synchrotron foregrounds $> 10^3$ signal
• HI content, distribution at high-z uncertain

Haslam Map at 408 MHz
HI Intensity Mapping Current Status
Pilot Program at Green Bank Telescope

- HI: $0.58 < z < 1.0 \rightarrow 900 \text{ MHz} > \text{frequency} > 700 \text{ MHz}$
- GBT Beam FWHM $\sim 15'$ $\rightarrow 9 \, h^{-1}\text{Mpc} \text{ at } z \sim 0.8$ Ideal for large-scale structure studies
- Spectral resolution $\sim 24 \text{ kHz}$, rebinned to $\sim 500 \text{ kHz} \rightarrow 2 \, h^{-1}\text{Mpc}$ Ideal for large-scale structure studies

GBT radio continuum sources + HI

GBT HI

DEEP2 density

Chang+ 2010
HI Intensity Mapping Current Status

Current limits on 21 cm auto power spectrum and measurements on $\Omega_{\text{HI}}b_{\text{HI}}$ at $z=0.8$ using the GBT by our GBT-HIM science team.

\[\Omega_{\text{HI}}b_{\text{HI}} = [0.62^{+0.23}_{-0.15}] \times 10^{-3}\]
BAO with HI IM

- Signals are on large-scales (150 Mpc comoving)
- HI signals are weak, ~100 microK (z)
- Need high-surface brightness sensitivity at core, similar to EoR requirements (~100-300m baselines depending on redshifts)
- Errors on BAO distance scales prop to (core filling factor)^{-1}.
- SKA1-mid, f\sim 0.03 (<400m)
- SKA1-sur, f\sim 0.003 (<400m)
- SKA1-low, f\sim 0.91 (<220m)
BAO signals (150 Mpc) resolved in 3D (with a 100m baseline)

<table>
<thead>
<tr>
<th>z</th>
<th>freq (MHz)</th>
<th>d_{comoving} (Mpc)</th>
<th>dz</th>
<th>dfreq (MHz)</th>
</tr>
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<tr>
<td>0.8</td>
<td>789</td>
<td>10.55</td>
<td>0.0038</td>
<td>1.66</td>
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<td>1</td>
<td>710</td>
<td>13.93</td>
<td>0.0056</td>
<td>1.98</td>
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<td>33.04</td>
<td>0.022</td>
<td>3.45</td>
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<td>2.5</td>
<td>406</td>
<td>43.46</td>
<td>0.036</td>
<td>4.13</td>
</tr>
<tr>
<td>3.5</td>
<td>316</td>
<td>68.72</td>
<td>0.077</td>
<td>5.31</td>
</tr>
</tbody>
</table>

Short baselines (100-500m), low spectral resolution (< 0.1 MHz)
Other constraints

• Need to subtract foregrounds to high accuracy (better than 0.1%)
  • requires polarization purity (so polarized foregrounds won’t leak into I).
  • no bandpass frequency structures > MHz scales that may mimic HI signals
  • may require large instantaneous FoV, similar to EoR concerns
  • OH megamaser contamination?
BAO measurements

Forecasts on Baryon Acoustic Oscillation (BAO) distance scale.
BAO measurements with HI IM

Forecasts on Baryon Acoustic Oscillation (BAO) distance scale.

z~3.5, 5000hrs, 500 deg$^2$
Summary

• 21cm Intensity Mapping for BAO measurements is a new and promising field

• Dedicated instruments/telescopes (GBT-HIM, CHIME, Tian-Lai) are under-construction for this science goal.

• SKA1-mid and -sur may not be competitive for BAO measurements at z<3 (*need to be verified). It will be very useful if central core (<100m) is packed.

• SKA1-low may have a unique measurement at high-z, probing alternative dark energy models and large-scale structure (for e.g., Omega_k and neutrino masses), but foregrounds will be challenging.