3D Intensity Mapping & 21 cm cosmology

Réza Ansari

SKA-LOFAR radio days
IAP (Paris) February 2014
Dark energy & BAO at 21 cm
- DE and BAO
- Galaxies at 21 cm at cosmological distances

Intensity mapping
- 3D mapping of 21 cm emission
- Sensitivity to P(k) measurement
- Foregrounds: extracting cosmological signals

BAORadio: intensity mapping R&D in France

CHIME, TIANLAI ... SKA (AA-mid)
Dark energy & BAO
BAO : Baryon Acoustic Oscillations

- Imprints left by the baryon-photon plasma oscillations prior to decoupling, on dark matter and visible matter (galaxies ...) during structure formation after decoupling

- Wiggles in the distribution of matter, dominated by dark matter (and also visible matter / galaxies): A preferential length scale (~150 Mpc) in the matter clustering

- Standard ruler type cosmological probe with a measurement @ z ~ 1100 (CMB anisotropies)
Acoustic Oscillations seen in CMB

Characteristic scale $\sim 150$ Mpc

Galaxy distribution
$(z, \text{angle } (\alpha, \delta))$ plane

BAO: Imprints of photon-baryon plasma oscillations in galaxy distribution
SDSS-III BOSS DR9/10/11 galaxy power spectrum & correlation function

Anderson et al, arXiv 1312.4877

$z \sim 0.57$ (BOSS) $\Rightarrow z \sim 0.5 \ldots 3$ in future surveys

---

**Figure 10.**

Top panel: The measured monopole of the CMASS galaxy correlation function, multiplied by the square of the scale, $s$, for each of the BOSS data releases. These figures are shown pre-reconstruction. For clarity, the DR10 data have been shifted horizontally by $+1\, h^{-1} \text{Mpc}$ and the DR9 data by $+1\, h^{-1} \text{Mpc}$. Bottom panel: The measured spherically averaged CMASS galaxy power spectrum, multiplied by the frequency scale, $k$, for each of the BOSS data releases. For clarity, the DR9 data have been shifted by $+0.002\, h \text{Mpc}^{-1}$ and the DR10 data by $+0.002\, h \text{Mpc}^{-1}$. All of the error-bars shown in both panels represent the diagonal elements of the covariance matrix determined from the mocks. One can observe broadly consistent clustering, especially in the overall shape of each curve.

---

**6.2 DR11 Acoustic Scale Measurements**

Our BAO measurements are listed in Table 7. The mocks for DR10 and DR11 show significant improvement with reconstruction in most realisations, and we therefore adopt the reconstruction results as our default measurements. Our consensus value for the CMASS BAO measurement, $\xi_{\text{BAO}} = 1.0144 \pm 0.0089$, is determined from a combination of $P(k)$ and $\xi(s)$ measurements, and in what follows we describe the process of obtaining this value, and tests that validate it.

Post-reconstruction, the significance of the BAO detection in both the correlation function and the power spectrum are greater than 7 for the reconstructed DR11 CMASS BAO measurements. The significance of detection is shown in Fig. 12, where we also see a difference in the detection significance between results from $\xi(s)$ and $P(k)$. This variation is caused by the differential ability of the models for the broad-band component to match the offset between the data and the no-baryon model. The broad-band model for the power spectrum has more free parameters than that for the correlation function, so it is perhaps not surprising that the no-baryon model is a slightly better fit.

Table 7 also lists $\chi^2$/dof for the best-fit models, showing that they are close to unity for DR10 and DR11 fits using both the correlation function and power spectrum. The most unusual is the $\chi^2$/dof = 18/27 for the post-reconstruction DR11 $P(k)$ measurement.
Baryon Acoustic Oscillations

Slide borrowed from A. Stebbins
Large scales: $\beta_r = 7.5$ at $z=1$ degrees

Small scales: $300 - 100 - 30 - 10$ $1/h$ Mpc

non linear regime

Clusters: $\sim 8$ Mpc


$P(k) [(h^{-1}$ Mpc$)^3]$
BAO in radio

As in optical surveys:

- Identification of H\textsc{i} (21 cm) emission sources, determination of the angular position and redshift - Computation of the two point correlation function or the P(k) spectrum, using the catalogue of identified objects.

Or similar to CMB observations:

- 3D mapping of the H\textsc{i} (21 cm) emission - T21(\alpha,\delta,z) - Radio foreground subtraction, determination of the power spectrum P(k,z) on the 21 cm sky temperature data cubes.
LSS / BAO in radio with galaxies

\[ S_{21}^{Jy} \approx 0.021 \times 10^{-6} \, \text{Jy} \ \frac{M_{HI}}{M_\odot} \times \left( \frac{1 \text{Mpc}}{D_L} \right)^2 \times \frac{200 \, \text{km/s}}{\sigma_v} (1+z) \]

\[ S_{lim} = \frac{2 \, k \, T_{sys}}{A \sqrt{2t_{integ} \Delta \nu}} \]

\( S_{lim} \) en \( \mu \text{Jy} \) pour \( t_{integ} = 86400 \, \text{s} \), \( \Delta \nu = 1 \, \text{MHz} \)

\( S_{21} \) en \( \mu \text{Jy} \) pour \( M_{HI} = 10^{10} M_\odot \)

<table>
<thead>
<tr>
<th>A (m^2)</th>
<th>Tsys (K)</th>
<th>Slim</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>50</td>
<td>66</td>
</tr>
<tr>
<td>5000</td>
<td>25</td>
<td>33</td>
</tr>
<tr>
<td>100000</td>
<td>50</td>
<td>3.5</td>
</tr>
<tr>
<td>100000</td>
<td>25</td>
<td>1.7</td>
</tr>
</tbody>
</table>

\[
S_{lim} = \frac{2 \, k \, T_{sys}}{A \sqrt{2t_{integ} \Delta \nu}}
\]

\( > 100\,000 \, \text{m}^2 \rightarrow \text{Need SKA!} \)
\[ 21 \text{ cm line is } \pm \text{ is the only spectral feature around 1 GHz} \]\noindent spectro-photometric observations
\[ \text{Band: } \sim 100 \text{ MHz } \ldots 1500 \text{ MHz } - \nu = f(z), z: 0 \ldots 10 \]
\[ 1420 \text{ MHz } @ z=0, 946 \text{ MHz } @ z=0.5, 720 @ z=1, 284 @ z=5, 129 @ z=10 \]
\[ \text{Diffraction limited, source confusion:} \]
\[ 700 \text{ MHz: } D=100 \text{ m } \rightarrow \sim 20', \ D=1 \text{ km } \rightarrow \sim 2', \ D=100 \text{ km } \rightarrow \sim 1''', \ 2' \rightarrow 1 \text{ Mpc } @ z = 1 \]
\[ \text{Intensity measurement in optical, amplitude & phase in radio; } \]
\[ \text{CCD in optics, but interferometry and spectroscopy in radio} \]
\[ \text{instrumental noise (read-out noise } < 5 \text{ e) often négligeable in } \]
\[ \text{optical, dominant in radio (Tsys} \sim 20-50 \text{ K}) \]
\[ \text{low ambient / parasitic light level in optical in good observatories; } \]
\[ \text{radio band polluted (RFI) by terrestrial emissions} \]
Intensity mapping & dark energy surveys
3D mapping of neutral hydrogen distribution through total 21 cm radio emission (no source detection)

Needs only a modest angular resolution 10-15 arcmin

Needs a large instantaneous field of view (FOV) and bandwidth (BW)

Instrument noise (Tsys)

Foregrounds / radio sources and component separation

- Peterson, Bandura & Pen (2006)
- Chang et al. (2008) arXiv:0709.3672
- Ansari et al (2012)
Haslam 408 MHz map (Galactic synchrotron emission)

Signal HI: $T_{21} < \text{mK}$!
Radio foreground (GSM) @ 720 MHz (z=1.) - Kelvin

21 cm sky brightness @ 720 MHz (z=1.) - milliKelvin

Tsys ~ 50 K
mK sensitivity with $T_{sys} \sim 50-75$ K

- Large integration time ($10^4$-$10^5$ s) $\propto 1/\sqrt{t_{\text{int}} \Delta \nu}$
- Instrument ($T_{sys}$, beam ...) stability
- multi beam - large FOV radio telescope
- interferometer or FPA/multi feed receivers with single dish
$P(k)@21\text{ cm} - P\text{Noise}(k)$

$P(k)-21\text{cmLSS } z=1.0$
(a) 100m Dish, 10 beams
(b) 100m Dish, 100 beams
(b) 50m Dish, 100 beams
(d) 11x11=121x[D=5m]

- $z = 1$ ($v \approx 710\text{ MHz}$)
- 10 000 sq.deg ($\pi\text{ srad}$)
- 1 year observation
- $T_{\text{sys}} = 50\text{ K}$

R. Ansari - Sep 2011
Foreground removal

- Exploit frequency smoothness and power law ($\propto v^\beta$) behavior of foregrounds (synchrotron/radio sources)

- power law / polynomial / foreground model fit & subtraction

- Mode mixing, bias, error propagation …
Mode Mixing

High frequency

Low frequency

Frequency dependent beams

Low frequency

High frequency

intensity

frequency

intensity

frequency

Slide by Kris Sigurdson
UBC
Signal-to-Noise Eigenmodes

- Measurement $v$ is a combination of the sky $a$ and noise $n$

$$v = Ba + n$$  \hspace{1cm} (1)

- Construct the covariances of the signal and foregrounds

$$S = B \left\langle a_s a_s^\dagger \right\rangle B^\dagger, \quad F = B \left\langle a_f a_f^\dagger \right\rangle B^\dagger$$  \hspace{1cm} (2)

- Jointly diagonalise both matrices (eigenvalue problem)

Karhunen-Loève (KL) Transform: \hspace{1cm} $Sx = \lambda Fx$  \hspace{1cm} (3)

- Gives a new basis, where we expect that all modes are uncorrelated. Eigenvalue $\lambda_i$ gives ratio of signal to foreground variance for mode $i$.


Richard Shaw, Ue-Li Pen Kris Sigurdson et al.  
Mapping cosmic matter distribution using neutral hydrogen as tracer

Measure the $\text{H}_\text{I}$ density fluctuations and its power spectrum $P_{21}(k)$

Determine BAO scale $k_{\text{BAO}}$ pour $0.5 < z < 2-3$

Measure the $\text{H}_\text{I}$ gas fraction as a function of redshift, scale and environment

Mapping of the radio foregrounds in the 500-1000 MHz band

21 cm BAO vs optical redshift survey
10 000 sq.deg, 3 years survey, 5 redshift bands (0.5 1.0 1.5 2.0 2.5)
10 000 m² collecting area, 400 beams

• In France, BAORadio project started in 2007

• LAL (IN2P3/CNRS), Irfu (CEA), Observatoire de Paris

• Development of the BAORadio analog & digital electronic system

• Focal plane array prototype FAN

• Electronic tests at Nançay, using the large radio telescope

• Test using the CRT prototype at Pittsburgh

• PAON test interferometer with small dishes

• Financial support: IRFU, CNRS/P&U, P2I, Obs. de Parius, LAL, PNCG
BAORadio (french 21cm intensity mapping effort)

- Electronic, acquisition & processing software development
- FAN (J.M.Martin, P. Colom)
- Observations with CRT at Pittsburgh, calibration and beam synthesis
- HI-Cluster wide band observation program with NRT (publication in preparation - 2014)
- OptX21 wide band observations with NRT: BAORadio & WIBAR
- PAON test interferometer at Nançay
- NEBuLA - wide band digitizer (C. Viou, D. Charlet)
Test interferometer for an array of small dishes (RAID concept)
PAON-2 : $2 \times D=3$ m dishes (sep 2012 - sep 2013)
PAON-4 : $4 \times D=5$ m dishes, construction phase
deployment : nov 2013 - march 2014

PAON
Paraboles A l’Observatoire de Nançay

PAON-2, CasA transit,
(Oct 2012) Tsys ~ 120 K
PAON Test Interferometer
(J.M.Martin, J.E. Campagne)

PAON-2
installed September 2012

PAON-4
(F. Rigaud)
installation Nov 2013 - March 2014
4 D=5m dishes
Transit de

CygA

Observations de Cyg A durant 4h [1250-1500] MHz

Sigma -> $T_{sys}$

$T_{sys} \sim 100K$

1400MHz

NRT: 50K
Avant-plans ~ O(K)
Signal HI O(mK)

Slide by J.E. Campagne
Other 21 cm BAO projects

- LOFAR
- GMRT
- MWA
- SKA-LOW
- HERA
- CHIME
- Tianlai
- GBT
- BAOBab
- SKA-mid

- z = 100 to 20
  15 to 70 MHz

- z = 20 to 5
  70 to 240 MHz

- z = 5 to 0
  240 to 1400 MHz
Canadian Hydrogen Intensity Mapping Experiment (CHIME)
The CHIME Pathfinder

Slide by K. Bandura
**CHIME Fact Sheet**

### Full CHIME Layout

<table>
<thead>
<tr>
<th>Structure</th>
<th>5 cylinders, 100m x 20m each</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>400-800 MHz</td>
</tr>
<tr>
<td>Number Feeds/cylinder</td>
<td>256 dual pol feeds per cylinder (2560 digitizers total)</td>
</tr>
<tr>
<td>Frequency Channels</td>
<td>512 frequency channels, 781 kHz wide (1.28 μs) (for cosmology, you can channelize further!)</td>
</tr>
<tr>
<td>Data Rate</td>
<td>$2N_{\text{FEEDS}} \times 3.2 \text{ Gbit/s} = 8 \text{TeraBit/s}$ (assumes 4bit truncation)</td>
</tr>
</tbody>
</table>

### Observing Frequency

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>400 MHz</th>
<th>to</th>
</tr>
</thead>
<tbody>
<tr>
<td>75 cm</td>
<td>400 MHz</td>
<td>800 MHz</td>
</tr>
<tr>
<td>37 cm</td>
<td>800 MHz</td>
<td></td>
</tr>
<tr>
<td>21 cm Redshift</td>
<td>z=2.5 (11 Gyr ago)</td>
<td>z=0.8 (7 Gyr ago)</td>
</tr>
<tr>
<td>Beam Size</td>
<td>0.52°</td>
<td>0.26°</td>
</tr>
<tr>
<td>E-W FoV</td>
<td>2.5°</td>
<td>1.3°</td>
</tr>
<tr>
<td>N-S FoV</td>
<td>-45° to +135° (max possible)</td>
<td>0° to +90° (more likely)</td>
</tr>
<tr>
<td>Time/pixel/day</td>
<td>10min, 14min, 24hrs equator, 45deg, ncp</td>
<td>5min, 7min, 24hrs equator, 45deg, ncp</td>
</tr>
</tbody>
</table>

### Receiver Noise Temperature
- 50k
- -2K / Jy

### Daily Sensitivity
- ~50 μJy / pixel
- ~1.5 μJy/pixel

*(Approximate – for planning purposes only)*

---

16 channel correlator now, 256 channel correlator by spring 2014

---

*Slide by K. Bandura*
From CRT / BAORadio to…

Tianlai

Toward a large instrument for 21 cm DE survey

• Tianlai project led by NAOC (China) - Prof. Xuelei Chen
• TDA (Tianlai Dish Array) and PC-GPU correlator (US, P. Timbie, J. Peterson)
• PAON demonstrator
Tianlai site (Xinjiang, western China)
Tianlai site: Hongliuxia  
(Xinjiang, western China)  
44.15 N, 91.8 E

① Xingjiang - Hongliuxia  
② Xingjiang - Dashankou  
③ ④ Inner Mongolia, Baichi
Tianlai correlator & ADC boards
Development plan for the Tianlai 21 cm DE survey

- 2014-2015: TDA (Tianlai Dish Array), 16 D=6m dish array
- 2015: CRT type instrument (3 Cylinder array)
- 2015: Stage 1 - engineering array, 32 feeds
  * Aim: detect optical $\times$ 21cm cross correlation at $z \sim 0.7-1$
- 2016: Stage 2 - first science array, $\sim$ 200 feeds (2016-2018)
  * Aim: detect BAO with 21 cm signal at $z \sim 0.7 - 1.0$
- 2020?: Stage 3 DE survey, $\geq$ 1000 feeds
  * Aim: measure BAO with 21 cm signal in the redshift range 0.5...2.0
Outlook

• Exciting scientific perspectives (DE, H\textsubscript{i} mass distribution at $z \sim 1.5$ ...) for intensity mapping surveys

• CHIME, Tianlai can serve as testbeds to develop intensity mapping and open the way for larger instruments (SKA-mid, Aperture Arrays)

• Scientific challenge: data processing, 3D map making & foreground subtraction
Intensity mapping workshop:
Paris Observatory/CIAS, 4-6 June 2014

* 1 to 2 days OPEN MEETING ON INTENSITY MAPPING
* 1 day Tianlai collaboration workshop
* June 7 visit of Nançay radio astronomy station
Organization: JM.Martin (GEPI), R.Anzari (LAL), CIAS
Announcement soon via SF2A, PNCG, list SKA-LOFAR

Focal Array at Nançay (FAN) workshop:
Paris Observatory/CIAS, end of May 2014 (TBC)
* 1 day workshop

→ discussion of the scientific case for a multibeam receiver
for the Nançay decimetric Radio Telescope (NRT)
Organization: JM.Martin (GEPI), P.Colom (LESIA), CIAS
Announcement via SF2A, SKA-LOFAR lists