Future Science Possibilities for the WSRT:

Aperture Synthesis enters the Focal Plane Array Era

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Outline

• background
• Focal Plane Array receivers and back-ends
• new capabilities
  • overview
  • eg. constraining dark energy
  • eg. imaging the low red-shift cosmic web
Background

- WSRT collecting area (50% VLA) is competitive at those frequencies where it can be efficiently illuminated and the surface is sufficiently reflective ($\nu = 150 \text{ MHz} - 2400 \text{ MHz}$)
- WSRT “market niche” is (red-shifted) HI and (polarimetric-) continuum imaging with high surface brightness sensitivity
- also: tied-array pulsar observing and VLBI participation
Aperture Synthesis enters the Focal Plane Array Era

To what extent can existing telescope’s FOV be extended?

- simulations for a $f/D = 0.35$ parabola show good illumination ($\eta > 0.8$) possible over a field with diameter of about 10 FWHM if $\sim 6.5\lambda$ diameter field is fully-sampled (or $\sim 5$ FWHM for $3.3\lambda$)
- full sampling requires about $\lambda/3 - \lambda/4$ spacing
- $\Rightarrow$ about 100 elements for $3.3\lambda$ circle (0.8 m @ 1200 MHz)
- yields $\sim 25$ times the FOV with high $\eta$ in all beams

$1.3$ m prime focus circle yields $\sim 10$ FWHM @ $f/D = 0.35$ (WSRT)
Proposed FPA System Parameters

• Frequency Band: 850 – 1750 MHz (bottom end by TV RFI, top end from OH lines)
• Dual Polarization
• Instantaneous BW: minimum of 320 MHz (to be competitive with other L-band systems) preferred goal of 1 GHz (ie. entire band)
• Tsys < 50 K, $\eta_A > 70\%$
• Freq. resolution: 20 kHz over full BW or finer for smaller BW (corresponds to 4 km/s for the HI line)
• Instantaneous FoV: 25 primary beams (formed from the 100 elements of each FPA)
• Correlation: 14*14 for each of 25 beams, full polarization
• Wide-field application efficiency: 25/4 = 6 x EVLA
What will become possible?

- Survey programs are **50 times faster, so 7 times deeper** in the same total integration time.
- Continuum Sensitivity: < 7 \( \mu \)Jy in 12 hours over 13 \( \text{deg}^2 \)
  - 20 \( \mu \)Jy 130 \( \text{deg}^2 \)
  - 70 \( \mu \)Jy 1300 \( \text{deg}^2 \)
  - spanning 850 – 1750 MHz => RM synthesis, spectral shape.

- **Orphan GRB’s**
  - 1 GRB / day in \( \gamma \)-rays, but those are only the beamed ones.
  - 10-100 “orphan” GRB’s/day.
  - radio lifetime of \( \sim 1 \) month, peak radio flux \( \sim 100 \ \mu \text{Jy} \).
  - weekly imaging of same 130 \( \text{deg}^2 \) should yield \( \sim 5 \) simultaneous orphans above detection limit per epoch.
What will become possible?

**The Scintillating Universe**

- Scintillation on minute to hour scales (like J1819) yield source properties on 10's of flat spectrum AGN per deg\(^2\) at 100 \(\mu\)Jy level @\(\mu\)arcsec scales and detailed foreground screen parms.

**The Magnetic Universe** (confusion limit in Q,U,V perhaps 1 \(\mu\)Jy)

- Produce RM grid from Galactic pulsars plus background AGN at various distances; with 7 \(\mu\)Jy rms (12 hr obs) get detected polarized source density of \(~100\) deg\(^{-2}\)

- Precision mapping of Galactic B field, nearby galaxy B fields, cluster B fields (eg. Perseus) and first chance to detect IGM inter-cluster B filaments
What will become possible for Pulsars?

Survey Figure of Merit: \( M = \text{FoV} \times (\frac{A}{T})^2 \times \text{BW} \times \nu^{-3.6} \)

<table>
<thead>
<tr>
<th>Antenna Type</th>
<th>FoV (deg(^2))</th>
<th>A/T (m(^2)/K)</th>
<th>BW (MHz)</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arecibo 20 cm ALFA 7-bm</td>
<td>0.019</td>
<td>1240</td>
<td>300</td>
<td>2.6x10(^6)</td>
</tr>
<tr>
<td>Parkes 20 cm 13-bm</td>
<td>0.41</td>
<td>107</td>
<td>300</td>
<td>4.2x10(^5)</td>
</tr>
<tr>
<td>Parkes 70 cm</td>
<td>0.39</td>
<td>49</td>
<td>32</td>
<td>7.6x10(^5)</td>
</tr>
<tr>
<td>WSRT 20 cm FPA-grate</td>
<td>13</td>
<td>196</td>
<td>300</td>
<td>1.5x10(^8)</td>
</tr>
<tr>
<td>WSRT 90 cm 8-grate</td>
<td>4.2</td>
<td>47</td>
<td>10</td>
<td>5.6x10(^6)</td>
</tr>
</tbody>
</table>

~70 times the 2005 state-of-the-art at 20 cm!!
Constraining Dark Energy

- WMAP (first-year) image of CMB fluctuations defines current state-of-the-art

Constraining Dark Energy

- CMB data provide excellent constraints on model params. assuming $\Lambda$CDM cosmologies
- **BUT** direct constraints on dark energy ($w=p/\rho$) are weak


Constraining Dark Energy

- acoustic oscillations at harmonics of the sound horizon at de-coupling (WMAP: $r_s = 144 +/- 4$ Mpc) also leave imprint on the baryonic power spectrum.
- only holds in linear regime, ie. $k < k_{\text{max}}(z)$, $z \sim 1$ is desirable.

Constraining Dark Energy

- very good prospects for determination of $w(z)$ with galaxy surveys
- optimum strategy is to aim for diagonal in $(N,V)$ measurement space (trade-off of cosmic variance versus shot noise)
- benchmark is SDSS with $\sim 10^6$ galaxies over $\sim 10^4 \text{ deg}^2$ at $z < 0.2$
- goal is $\sim 10^6$, $z \sim 1$ galaxies over $\sim 300 \text{ deg}^2 \Rightarrow V/V_{\text{sloan}} \sim 4$


$V_{\text{sloan}} \sim 2 \times 10^8 h^3 \text{ Mpc}^3$


$10\%$ $5\%$ $3\%$ $2\%$ error in $w$

at $z = 1$
Constraining Dark Energy

What will be possible?

- (2008+) WSRT 25-beam FPA (13 deg$^2$ FOV)
  - could get $\sim 10^6$ galaxy in 2x10$^4$ deg$^2$ at $z < 0.25$ in 3 year survey
- (20??) SKA (100x current sensitivity, 1 deg$^2$ FOV)
  - could get $\sim 1.5\times10^6$ galaxy in 400 deg$^2$ at $z < 1.5$ in 50 day survey
- (2010-2020) dedicated optical 8m class with multi-object spectrograph

Imaging the low-z Cosmic Web


- high res. num. sim. predict cosmic web of filaments between galaxies
- apparent correspondence with QSO absorbers
Imaging the low-z Cosmic Web

- strong (density-dependent) evolution with cosmic epoch
- collapse of over-dense regions yields greater proportion of WHIM (z=0)

~30% baryons in galaxies ( @ z = 0 )
- association with QSO absorbers with $N_{\text{HI}} = 10^{18} - 10^{22} \text{ cm}^{-2}$

~30% baryons in warm-hot inter-galactic medium (WHIM)
- condensed, shock-heated phase: $T \sim 10^5 - 10^7 \text{ K}$
- association with QSO absorbers with $N_{\text{HI}} = 10^{14} - 10^{18} \text{ cm}^{-2}$
- ties in with evidence from FUSE OVI absorption (Sembach et al. 2003) for Galactic corona, $R > 70 \text{ kpc}$, $n \sim 10^{-4}-10^{-5} \text{ cm}^{-3}$

~30% baryons in diffuse inter-galactic medium
- diffuse, photo-ionized phase: $T \sim 10^4 \text{ K}$
- association with QSO absorbers with $N_{\text{HI}} = 10^{12} - 10^{14} \text{ cm}^{-2}$

decreasing (micro- not macro-) neutral fraction with $N_{\text{HI}}$
- $\sim 1\%$ at $N_{\text{HI}} = 10^{17} \text{ cm}^{-2}$, $< 0.1\%$ at $N_{\text{HI}} = 10^{13} \text{ cm}^{-2}$

role of “cold-mode” versus “hot-mode” accretion ???
ionization by intergalactic UV leads to exponential decline in neutral fraction: \( \sim 100\% \) to \( \sim 3\% \) from \( \log(N_{\text{HI}}) \sim 19.5 \) to \( \sim 18 \)

“HI desert” is major observational challenge!!

slow decline of neutral fraction below \( \log(N_{\text{HI}}) \sim 18 \)!!

• M31/M33 filament near systemic velocity, $N_{\text{HI}} \sim 4 \times 10^{17} \text{cm}^{-2}$ (peak)
Imaging the low-z Cosmic Web

The M31 – M33 filament

- connects $V_{\text{SYS}}$ of M31 and M33
- continues in anti-M33 direction (300 kpc total extent)
- filamentary structure within 30 kpc
- connects to ongoing fueling of both M31 and M33


wide-field WSRT data
Imaging the low-z Cosmic Web

The M31 – M33 filament

• extremely diffuse in bridge region
  (same low $N_{\text{HI}}$ in GBT and WSRT TP beams)

GBT confirmation (30 min ON/OFF)

wide-field WSRT data

⇒ the first detection of the “cosmic web”/ WHIM in HI emission

Imaging the low-z Cosmic Web

The M31 – M33 filament

- clump spectrum, $\sigma \sim 13$ km/s $\Rightarrow T_k \sim 20,000$ K
- average spectrum over 4x3 deg, $\sigma \sim 45$ km/s
  - velocity field sub-structure yields $\sigma < 20$ km/s
  - looks like $T_k \sim 2\times10^5$ K (possibly hot-mode accretion)

$\triangleright$ condensations in the WHIM
Imaging the low-z Cosmic Web


- composite $N_{\text{HI}}$ distribution from WSRT mosaic, GBT, wide-field WSRT
- normalization from HIPASS BGC (Zwaan et al. 2003, AJ, 125, 2842)
  - good agreement with QSO absorption line data
  - confirmation of 30-fold increase in covering factor $10^{19} - 10^{17} \text{ cm}^{-2}$
  - the first image of a Lyman Limit absorption System
Imaging the low-z Cosmic Web

How can we go beyond the Local Group?

- require: $\Delta N_{\text{HI}} < 10^{18} \text{ cm}^{-2}$ over $\Delta V = 20 \text{ km/s}$, $D\theta < 20 \text{ kpc}$

First Glimpse

- (2005 – 2006) WSRT semi-shadowed mode survey of the super-galactic plane filament ($\alpha = 8 – 17 \text{ h}$, $\delta = 0 – +10^\circ$)
- simulate filled aperture by observing at extreme HA’s for $\delta = 0$ to $+10^\circ$: **grating array (12x144 m) becomes filled-aperture (25x300 m)** with spectral baseline quality of interferometer(!) and beam of 3 x 35 arcmin
- achieve $\Delta N_{\text{HI}} \sim 2 \times 10^{17} \text{ cm}^{-2}$ over $\Delta V = 20 \text{ km/s}$
Imaging the low-z Cosmic Web

- probe extended environments of > 340 galaxies within 40 Mpc with a 22,000 pointing mosaic
- survey (~1000 hr) begun in December 2004, now 45% complete
Imaging the low-z Cosmic Web

How can we go beyond the Local Group?

The Next Generation

• (2008+) WSRT 25-beam FPA
• will approach $\Delta N_{\text{HI}} \sim 10^{16} \text{ cm}^{-2}$
  over $\Delta V=20 \text{ km/s}$
• the next order of magnitude in surface covering factor
• background source density
  will allow (optical/UV/X-ray)
  absorption obs. of metallicity and ionization state

✔️ baryonic mass measurements and enrichment history