IPS and Solar Imaging

Divya Oberoi
MIT Haystack Observatory

1 November, 2006
SHI Meeting
Outline

- The low-frequency advantage
- Interplanetary Scintillation studies
- Solar Imaging
- An example from Early Deployment observations
- Prototype array
- Conclusion
The low frequency advantage

- Propagation effects due to solar wind become increasingly discernible below 1GHz
- Ionospheric propagation effects are (hopefully) manageable down to ~100 MHz
- Availability of useful astronomical sources
- ~100-300 MHz optimal
Low frequency technology

- Very wide fields of view
  - Simultaneous access to a large part of the sky
  - All sky imaging
- Essentially digital instruments
  - Impressive hardware capabilities at affordable prices
  - Large number of simultaneous independent beams
- Affordability of computation
  - Would not have been possible just 5 yrs ago
Interplanetary Scintillation (IPS)

- Plane wavefront incident from a distant compact source
- The density fluctuations in the Solar Wind act like a medium with fluctuating refractive index, leading to corrugations in the emerging wavefront
- These phase fluctuations develop into intensity fluctuations by the time they reach the observer
- The resulting interference pattern sweeps past the telescope, leading to IPS
IPS Geometry

A line-of-sight samples solar wind from

- an extended region on the solar surface (linear extent of \(~100^\circ\) )
- an extended window in time (few days)
Lines of sight in one solar rotation

If certain assumptions are satisfied, the IPS data can yield a tomographic reconstruction of the heliosphere.

Kojima, M., STELab
Space Weather Forecasting with Interplanetary Scintillation Data

- Velocity
- Density

Jackson and Hick (UCSD), Kojima (STEL)
Limitations of existing observations

- \(~40\) sources/day \(\sim 1000\) obs/Carrington rotation
  # constraints/# of free parameters \(\sim 1\)
  \(\Rightarrow\) reconstructions with \(6.5^\circ \times 6.5^\circ\) pixels
  - \(1^\circ \times 1^\circ\) resolution and 2 constraints per free parameter
  \(\Rightarrow\) 100 fold increase in number of observations

- Limits success to periods of low activity and simple solar wind structure

- Limited spatial and temporal sampling of the heliosphere
IPS with the MWA-LFD

- Wide fields of view + ~16 independent beams for each polarization
  ⇒ *Vastly improved heliospheric sampling - addresses the most constraining bottleneck*

- ~20,000 - 40,000 observations per Carrington rotation, compared to ~1000 currently available

- Better sensitivity than the existing dedicated IPS instruments ⇒ a larger number of sources will be accessible

- Better equipped to handle time evolution
The larger picture

- We will have
  - IPS (MWA-LFD) - $\int F(V, \delta n_e^2, \alpha) \, ds$
  - FR (MWA-LFD) - $\int n_e \mathbf{B} \, ds$
  - HI (SMEI/STEREO) - $\int n_e \, ds$

- Integral measures of different physical properties of the same medium – truly complementary information

- All these data should be used to simultaneously constraint a single self-consistent model

- The models are getting there...
Solar Imaging
The Sun...

- is a highly time and frequency variable source
- has a complex source structure
- needs reliable imaging of faint features in presence of bright features (high dynamic range imaging)
  - 500 tiles, compact configuration ⇒ Excellent instantaneous monochromatic Point Spread Function
- has emission at angular scales of up to ~degree
  - Many small baselines ⇒ Sensitivity to large angular scales
- MWA-LFD is very well suited for solar imaging
  - Angular resolution is bit smaller than the expected scatter broadening size
Type II bursts

- Complex and controversial relationship with flares, large space weather impact
- 100% association with flares and CMEs, though converse is not true
- Theoretical models
  - Shocks produced by the fast moving ejecta leads to the type II emission
  - Flare blast waves – sudden heating of coronal loops
- 5-15 min, 50-150 MHz, -0.2 MHz/s, 1/month (Sol max)
- 160 MHz: $T_B \sim 10^{11}$ K, $S \sim 10^8$ Jy
- Plasma emission at plasma frequency and its harmonic
- Extensively studied in frequency-time plane, but very few images

Fig. 4. Culgoora radioheliograph data of a type II source visible above the solar limb at two times separated by 19s (Smerd, 1970).
Let’s get a picture

- Imaging spectroscopy - spatially resolved radio images, with sufficient time cadence, trace out the evolution and location of the type II emission region
  - Comparison with Coronagraph images
- This is emission at $\nu_P$, propagation effects should be significant. Simultaneous imaging at $\nu_P$ and $2\nu_P$ will give us a good handle on that
- Could any fine spectral and temporal structures still remain to be discovered in solar burst emission?
Type III bursts

- 30 kHz - 1 GHz, 1-few s
- 170 MHz: $T_B \sim 10^8$ K, $S \sim 10^5$ Jy, -130 MHz/s
- F-H pairs are often seen
- Common whenever a moderately active region is visible

- Plasma emission at fundamental and harmonic
- Electron beams moving along open field lines ($0.2c < v < 0.6c$)
Early Deployment Experiments

- 4 campaigns, April - September 2005
- Mileura, Western Australia
- 80 – 327 MHz
- 3 Tiles
- Bandwidth – 4 MHz
MWA-LFD Solar Burst Observations

15 September 2005

04:53  04:56  04:59  05:03  05:06  05:10  05:13 UT

Each panel = 60 seconds
Res: 50msec

FREQUENCY
98.5-102.5 MHz
Res: 16 kHz

COLOR: signal amplitude in dB, spanning a range of ~12 dB.
The state of the Sun

- Region 808 – complex active region
- 53 C-class, 10 X-class and 3 M-class flares - more major flares than any other region in Solar Cycle 23 (12-18 Sep 2005)
- Significant decay evident in white light images since 14 Sep 2005
- C-class flare began at 0149 UT, data presented spans ~0200-0300 UT, September 16, 2005

13-Sep-05

![Solar Image](image)

[GOES Space Environment Monitor Graph]
Spatial distribution of burst emission

J. Kasper, MKI
A high time and frequency resolution surprise

- 1420 MHz, 4 MHz
- $\Delta \nu = 31$ kHz
- $\Delta \tau = 0.5$ ms
- $\Delta \theta = 0.5'$
- $T_B = 10^{11}$ K
- 1944 UT13-Sep, 05, 25min after a X1.5 Flare
- Not easy to explain in terms of conventional models
Direct Imaging of CMEs

- Image thermal bremsstrahlung and/or synchrotron from CMEs
- Optically thin synchrotron from 0.5-5.0 Mev e interacting with B ~0.1 to few gauss
- Multi-freq. observations provide independent constraints on electron density and magnetic field in the CME loops

Prototype Array

- **Goals**
  - Test-bed for the end to end system
  - Training set for calibration and algorithm development
  - Initial solar observations

- **At the LFD site**
  - 32 Tiles (4 nodes)
  - ~350m max baseline
  - Bandwidth, spectral and time resolution – TBD (4 MHz, 64 kHz, 50 ms)
  - Timeline – mid to end 2007
## Summary of capabilities

<table>
<thead>
<tr>
<th>Ver</th>
<th>Time</th>
<th>$\Delta \nu$ (64 kHz)</th>
<th>$\Delta \tau$ (50 ms)</th>
<th>$\Delta \theta$ (2′ @200 MHz)</th>
<th>Science goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>End 07</td>
<td>Yes</td>
<td>Yes</td>
<td>No (20′ @200 MHz)</td>
<td>Type III bursts</td>
</tr>
<tr>
<td>1</td>
<td>End 08</td>
<td>Yes</td>
<td>No (8 s)</td>
<td>Yes</td>
<td>Type II bursts, CMEs</td>
</tr>
<tr>
<td>2</td>
<td>?</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Type II, III, CMEs</td>
</tr>
</tbody>
</table>
Conclusion

- Over the next few years the MWA-LFD will grow in its capabilities and scope
- It will be a scientifically interesting instrument at every step along the way
- We are currently focused on the ‘core’ instrument
- The instrument design is intrinsically flexible, can potentially serve other science objectives in the longer term
- Encourage the community to think about how can MWA-LFD contribute to their research
- Collaboration to contribute to the core instrument, at least initially
IPS Source density

- **Cambridge IPS survey (81.5 MHz)**
  - 1789 sources (Dec range -10° to 83°, 58% of sky)
  - Sensitivity – 5 Jy total flux, ~0.3 Jy scintillating flux at 90° elongation
  - Source size 0.2” – 2”

- **Puschino IPS survey (102 MHz)**
  - Artyukh and Tyul’bashev, 1996, Astronomy Reports, 42, 601
  - 414 sources in 0.144 sr (1 source/1.14 deg²)
  - Sensitivity – 0.1 Jy
  - 50% of sources < 3”

- **Ooty Radio Telescope (327 MHz)**
  - Manoharan, 2006, Solar Physics, 235, 345-368
  - Observe ~700 sources per day
  - Sensitivity – 0.04 Jy (1 sec, 4 MHz)
IPS Survey parameters

- **Cambridge Survey (81.5 MHz)**
  - 4096 full-wave dipoles
  - Beam – 26.8’ x 165’ Sec(z)
  - Bandwidth – 10.7 MHz

- **Puschino Survey (102 MHz)**
  - Physical collecting area – 70,000 m²
  - Beam – 49’ x 26’ Sec(z)
  - Bandwidth – 160 kHz

- **Ooty Radio Telescope (327 MHz)**
  - Effective collecting area – ~8,000 m²
  - Beam – 105’ x 3.5’ Sec(δ)
  - Bandwidth – 4 MHz
\[ B_k(\nu,t) = \sum_i \{ w_i \nu_i(\nu,t) \times G_{inst}(\nu,t-\tau_1,i,\text{pol},\theta_k,\phi_k) \times \phi_{iono}(\nu,t-\tau_2,\theta_k,\phi_k) \} \]

2G samples/s

\[ B_{IPS,k}(\nu',t') = \sum_{\Delta t} \sum_{\Delta v} B_k(\nu,t) B_k^*(\nu,t) \]

Detection and averaging in time and frequency

Pulsar interface
IPS tomography

- Tomographic IPS studies have been attempted
- Results – encouraging, but fall short of expectations and requirements

Geometric projections of ~800 lines-of-sight observed during Carrington rotation 1923.
IPS Tomography

- Minima of Cycle 23 (May-Aug 97)
- Spanned 4 Carrington rotations
- ~1,500 hours of observation
- ~700 observations per Carr. Rot

Good S/N observations
~15 min on source/obs

# MWA-LFD Design Goals

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency range</td>
<td>80-300 MHz</td>
</tr>
<tr>
<td># Tiles (receptors)</td>
<td>500 (8000)</td>
</tr>
<tr>
<td>Collecting area</td>
<td>8000 m² (at 200 MHz)</td>
</tr>
<tr>
<td>Field of View</td>
<td>15°-50°</td>
</tr>
<tr>
<td>Configuration</td>
<td>Core array ~1.5 km diameter (95%) + extended array ~3 km diameter (5%)</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>220 MHz (Sampled); 32 MHz (Processed)</td>
</tr>
<tr>
<td># Spectral channels</td>
<td>1000</td>
</tr>
<tr>
<td>Temporal resolution</td>
<td>8 sec</td>
</tr>
<tr>
<td>Polarization</td>
<td>Full Stokes</td>
</tr>
<tr>
<td>Point source sensitivity</td>
<td>20 mJy in 1 sec (32 MHz, 200 MHz)</td>
</tr>
<tr>
<td>Multi-beam capability</td>
<td>16, per polarization</td>
</tr>
<tr>
<td>Number of baselines</td>
<td>124,750 (VLA has 435)</td>
</tr>
</tbody>
</table>