Signals in the Dynamic Radio Sky
from LOFAR and other telescopes

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Time domain astronomy

- We were always interested in time-domain sky
- In radio, it is relatively easy: lots of easy to manipulate photons
Still, even in the radio sky it took a while...

The Haslam et al. 408-MHz Survey (Effelsberg/Jodrell Bank/Parkes)

Static image is “hiding” a lot of interesting sources...!
If Glyn Haslam had had better time resolution...
The success story of time-domain astronomy

The discovery of pulsars in Cambridge in late 1967:
The success story of time-domain astronomy

Lots of extremely useful applications:

- Plasma physics and electrodynamics under extreme conditions
- Solid state physics: super-dense matter & Equation of State
- Stellar physics, core collapse, binary evolution
- Interstellar, intercluster (& intergalactic) medium
- Galactic structure and magnetic field
- High precision astrometry, planetary ephemerides
- Gravitational physics and tests of general relativity
- Gravitational Wave detection
- Cosmology
The known pulsar population

(Figure by C. Ng)

> 2200 radio pulsars
1.40 ms (PSR J1748-2446ad)
8.50 s  (PSR J2144-3933)

> 220 binary pulsars

Orbital period range
93.7 min (PSR J1311-3430)
5.3 yr  (PSR J1638-4725)

>20 “extragalactic” pulsars
in Large & Small Magellanic Clouds

Companions
MSS, WD, NS, Planets
incl. 1 Double Pulsar!
The steps involved in this conversion, and definitions of the conversion process, are as follows:

1. **Observe sources in ‘search mode’.** This involves setting up the telescope to detect any incoming signals from space. The data collected during this phase are stored for further analysis.

2. **Obtain TOAs.** Time of Arrival (TOA) is the moment when the signal is detected at the telescope. These times are critical for timing the pulses accurately.

3. **Convert SATs to BATs.** The telescope signal is converted from Site Arrival Time (SAT) to Barycentric Arrival Time (BAT). This correction is necessary because the signal travels through the Earth's atmosphere and can be affected by various factors, including atmospheric refraction and ionospheric effects.

4. **Time-stamp the data.** Once the TOAs and BATs are obtained, the data are timestamped to an accuracy of 80 ns. This timestamp is referenced to the time of the observation, with each second divided into 1000 units.

5. **Dedispersing the data.** The data are then dedispersed to account for the dispersion effect caused by the ionosphere. This process removes the dispersive delays and allows for accurate timing of the pulses.

6. **Cross-correlate the data.** Individual pulses are extracted from the data and cross-correlated with templates. The profiles are then averaged to produce total intensity, i.e. Stokes I. This process helps in identifying individual pulses from the data.

7. **Obtain the TOA at the telescope.** The TOA is determined to obtain the Time of Arrival at the telescope. This is referenced to the time stamp.

8. **Implicitly assume in timing analysis software.** This process is generally implicit in timing analysis software. It is important to note that this process is performed on a monthly basis since April 2009, with observations between October 2008 and March 2009, and regular observations at Parkes.
The telescope receives dual linear polarisations but these are of 256 MHz divided into 512 channels, sampled every 100 ongoing. In our observational setup we utilise a bandwidth approximately monthly observations since April 2009, which are between October 2008 and March 2009, and regular approx-sars timed using unstable average profiles) and will result in inappropriate for single-pulse timing (as it is for slow pul-sars, i.e. the site arrival time (SAT, aka topocentric arrival time), which is referenced to the time stamp. The steps involved in this conversion, and definitions of the dynamic radio sky

Keane et al. (2011)

By Tim Hankins

Max-Planck-Institut für Radioastronomie

The University of Manchester, Jodrell Bank Observatory

Figure 1. The transient 'phase space' with known sources identified. This is simply a plot of the radio (pseudo-)luminosity versus emission frequency. We have used a logarithmic scale for both axes, and a constant radio luminosity of 10^2 erg/sec. The horizontal line at 10^2 erg/sec corresponds to the luminosity of the Crab nebula, while the vertical line at 10^7 Hz corresponds to the radio frequency of the Crab nebula. The black line represents the positions of pulsars, while the red line represents the positions of radio transients. The green line represents the positions of radio continuum sources. The blue line represents the positions of radio continuum sources in the Milky Way. The purple line represents the positions of radio continuum sources in the Milky Way. The pink line represents the positions of radio continuum sources in the Milky Way.
The telescope receives dual linear polarisations but these are of 256 MHz divided into 512 channels, sampled every 100 ongoing. In our observational setup we utilise a bandwidth approximately monthly observations since April 2009, which are between October 2008 and March 2009, and regular approx-sars timed using unstable average profiles) and will result in inappropriate for single-pulse timing (as it is for slow pul-profiles are far from stable in phase. Phase stability is usu-

2.5 Observations & Timing

The transient 'phase space' with known sources identified. This is simply a plot of the radio (pseudo-)luminosity versus frequency (reported in the papers). The transient sample is selected to have a sufficient luminosity density to occupy the 'dynamic regime' of the radio sky. The sample is divided into two parts, one of which contains the coherent regime of the radio sky while the other contains the incoherent regime. The coherent regime is defined as that part of the radio sky in which the phase stability is greater than 0.001 radian, while the incoherent regime is defined as that part of the radio sky in which the phase stability is less than 0.01 radian. The transient sample is divided into two parts, one of which contains the coherent regime of the radio sky while the other contains the incoherent regime.

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The parameter space of the dynamic radio sky

Keane et al. (2011)

Kramer et al. (2006)

By Tim Hankins

Max-Planck-Institut für Radioastronomie
The telescope receives dual linear polarisations but these are of 256 MHz divided into 512 channels, sampled every 100 ongoing. In our observational setup we utilise a bandwidth approximately monthly observations since April 2009, which are between October 2008 and March 2009, and regular approx-coherent timing solution.

Here we outline the steps involved in progressing from a telescope signal to barycentred pulse arrival times and a coherent timing solution.

The transient 'phase space' with known sources identified. This is simply a plot of the radio (pseudo-)luminosity versus frequency with a logarithmic scale. The horizontal axis represents the luminosity and the vertical axis represents the frequency. The diagram shows the distribution of various sources such as pulsars, solar bursts, and solar DAM (Distantly Astronomical Nuclei).

The parameter space of the dynamic radio sky

Keane et al. (2011)

Kramer et al. (2006)

10^7 s

Over 16 orders of magnitude!

Lorimer et al. (2007)

10^{-9} s

10^{-3} s

By Tim Hankins

10^{-9} s

10^{-3} s

Max-Planck-Institut für Radioastronomie

The University of Manchester

Swire Hall

The Manchester Observatory
A Bright Millisecond Radio Burst of Extragalactic Origin

D. R. Lorimer, M. Bailes, M. A. McLaughlin, D. J. Narkevic, F. Crawford

Pulsar surveys offer a rare opportunity to monitor the radio sky for impulsive burst-like events with millisecond durations. We analyzed archival survey data and found a 30-jansky dispersed burst, less than 5 milliseconds in duration, located 3° from the Small Magellanic Cloud. The burst properties argue against a physical association with our Galaxy or the Small Magellanic Cloud. Current models for the free electron content in the universe imply that the burst is less than 1 gigaparsec distant. No further bursts were seen in 90 hours of additional observations, which implies that it was a singular event such as a supernova or coalescence of relativistic objects. Hundreds of similar events could occur every day and, if detected, could serve as cosmological probes.

The “Lorimer-Burst”
The “Lorimer-Burst”

A Bright Millisecond Radio Burst of Extragalactic Origin

D. R. Lorimer,1,2* M. Bailes,3 M. A. McLaughlin,1,2 D. J. Narkevic,3 F. Crawford4

Pulsar surveys offer a rare opportunity to monitor the radio sky for impulsive burst-like events with millisecond durations. We analyzed archival survey data and found a 30-jansky dispersed burst, less than 5 milliseconds in duration, located 3° from the Small Magellanic Cloud. The burst properties argue against a physical association with our Galaxy or the Small Magellanic Cloud. Current models for the free electron content in the universe imply that the burst is less than 1 gigaparsec distant. No further bursts were seen in 90 hours of additional observations, which implies that it was a singular event such as a supernova or coalescence of relativistic objects. Hundreds of similar events could occur every day and, if detected, could serve as cosmological probes.

Where does it come from?

- Localisation for single dishes limited to beamwidth
- For reliable identification of astrophysical origin, burst should appear in one and only one beam*
- Multi-beaming (poor-man’s image) essential

* unless it is extremely bright...

ratios greater than 4 with the use of a matched filtering technique (7) optimized for pulse widths in the range 1 to 1000 ms. The burst was detected in data taken on 24 August 2001 with DM = 375 cm−3 pc contemporaneously in three neighboring beams (Fig. 1) and was located ~3° south of the center of the Small Magellanic Cloud (SMC).

The pulse exhibited the characteristic quadratic delay as a function of radio frequency (Fig. 2) expected from dispersion by a cold ionized plasma along the line of sight (8). Also evident was a significant evolution of pulse width across the observing frequency band. The behavior we observed, where the pulse width \( W \) scales with frequency \( f \) as \( W \propto f^{−1.8 \pm 0.4} \), is consistent with pulse-width evolution due to...
Pulses have some advantages: Dispersion

- The interstellar medium (ISM) is cold, ionized and magnetized plasma
- Pulses propagate with a frequency dependent group velocity:

  pulses are delayed wrt infinite frequency by:

\[ \Delta t = \frac{e^2}{2\pi m_e c} \int_0^d n_e \, dl = D \frac{DM}{\nu^2} \]

- The “Dispersion Measure” DM is a proxy for distance – in particular if \( n_e(l) \) is known
- We expect a characteristic \( 1/\nu^2 \) dependence for astrophysical pulses/bursts
But also: Pulse broadening due to interstellar scattering

Scattering time scales with $\Delta T \propto \text{DM}^{2.2} \nu^{-4}$

Example here: Magnetar just discovered in Galactic Centre (Eatough et al., Nature, 2013)
- Highest ever measured DM = 1778±3 pc cm$^{-3}$ - highly scattered a low frequencies
- Temporal broadening related to angular broadening – also observed
But also: Pulse broadening due to interstellar scattering

An astrophysical signal should be scattered as $v^{-4}$

Example here: Magnetar just discovered in Galactic Centre (Eatough et al., Nature, 2013)

- Highest ever measured DM = 1778$\pm$3 pc cm$^{-3}$ - highly scattered a low frequencies
- Temporal broadening related to angular broadening – also observed
Faraday rotation may also be observed

Rotation measure:

$$\text{RM} = \frac{e^3}{2\pi m_e^2 c^4} \int_0^d n_e B_\| dl$$

Faraday rotation:

$$\Delta \Psi = \text{RM} \times \lambda^2$$

DM and RM can give you an **weighted average** of the projected magnetic field:

$$\langle B_\| \rangle \equiv \frac{\int_0^d n_e B_\| dl}{\int_0^d n_e dl} = 1.23 \mu \text{G} \left( \frac{\text{RM}}{\text{rad m}^{-2}} \right) \left( \frac{\text{DM}}{\text{cm}^{-3} \text{ pc}} \right)^{-1}$$
Example, again: Galactic Centre Magnetar

- **New magnetar** = probe of Galactic Centre medium
- Highest DM of any pulsar: DM = 1778±3 cm⁻³ pc
- Source is ~ 100% linearly polarized.
- Rotation Measure RM = -66960±50 rad m⁻²
  
  largest RM measured in Galaxy (apart from Sgr A*)

LETTER

A strong magnetic field around the supermassive black hole at the centre of the Galaxy

R. P.Eatough¹, H. Falcé⁴, R. Karuppusamy⁷, K. J. Lee⁵, D. J. Champion¹, E. F. Keane⁷, G. Desvignes¹, D. H. F. M. Schnitzeler¹, L. G. Spitler¹, M. Kramer⁴, J. Klein⁴, C. Bassa⁷, G. C. Bower⁴, A. Brumhalter¹, I. Cognard¹, A. T. Butler¹, P. B. Demorest⁷, P. C. C. Freire¹, A. Kraus⁴, A. G. Lyne⁴, A. Noutsos², B. Stappers¹ & N. West¹

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The “Lorimer-Burst” - revisited

A Bright Millisecond Radio Burst of Extragalactic Origin

D. R. Lorimer, M. Bailes, M. A. McLaughlin, D. J. Narkevic, F. Crawford

Pulsar surveys offer a rare opportunity to monitor the radio sky for impulsive burst-like events with millisecond durations. We analyzed archival survey data and found a 30-jansky dispersed burst, less than 5 milliseconds in duration, located 3° from the Small Magellanic Cloud. The burst properties argue against a physical association with our Galaxy or the Small Magellanic Cloud. Current models for the free electron content in the universe imply that the burst is less than 1 gigaparsec distant. No further bursts were seen in 90 hours of additional observations, which implies that it was a singular event such as a supernova or coalescence of relativistic objects. Hundreds of similar events could occur every day and, if detected, could serve as cosmological probes.

- Appeared only in one beam
- With DM of 375 pc cm⁻³, much larger than Milky Way, but not so far from SMC pulsars
- Dispersion consistent with cold plasma law
- Dynamic range limited, but pulse appeared to be wider at lower frequencies
- Later Burke-Spolaor et. (2011) detected atmospheric origin of similar DM but not quite identical in properties

ratios greater than 4 with the use of a matched filtering technique (7) optimized for pulse widths in the range 1 to 1000 ms. The burst was detected in data taken on 24 August 2001 with DM = 375 cm⁻³ pc contemporaneously in three neighboring beams (Fig. 1) and was located ~3° south of the center of the Small Magellanic Cloud (SMC).

The pulse exhibited the characteristic quadratic delay as a function of radio frequency (Fig. 2) expected from dispersion by a cold ionized plasma along the line of sight (8). Also evident was a significant evolution of pulse width across the observing frequency band. The behavior we observed, where the pulse width W scales with frequency f as $W \propto f^{-3.8 \pm 0.4}$, is consistent with pulse-width evolution due to
Meanwhile...

The “Keane-Burst” (Keane et al. 2012)

- Discovered in archival data of the PMPS
- Near Galactic plane, b=-4 deg
- DM of 746 pc cm\(^{-3}\), while Milky Way less than 533 pc cm\(^{-3}\) in NE2001 model (Cordes & Lazio 2001)
- Consistent with cold-plasma law
- Considered: - giant pulse from pulsar
  - annihilating black hole
  - other models
- Possibly consistent with models if NE2001 is vastly wrong
- Problem: in the plane NE2001 sometimes simply not reliable...

Need better surveys and more detections...!
The all-sky “High Time-Resolution Universe Survey” (HTRU)

<table>
<thead>
<tr>
<th></th>
<th>Northern Survey</th>
<th>Southern Survey</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Start date</strong></td>
<td>Summer 2010</td>
<td>Early 2008</td>
</tr>
<tr>
<td><strong>Telescope</strong></td>
<td>Effelsberg-100m</td>
<td>Parkes-64m</td>
</tr>
<tr>
<td><strong>Sky coverage</strong></td>
<td>$\delta &gt; 0^\circ$</td>
<td>$\delta &lt; +10^\circ$</td>
</tr>
<tr>
<td><strong>Integration time</strong></td>
<td>Low-lat: 1500 s</td>
<td>Low-lat: 4300 s</td>
</tr>
<tr>
<td></td>
<td>Med-lat: 180 s</td>
<td>Med-lat: 540 s</td>
</tr>
<tr>
<td></td>
<td>High-lat: 90 s</td>
<td>High-lat: 270 s</td>
</tr>
<tr>
<td><strong>Receiver</strong></td>
<td>7-beam 1.4-GHz receiver</td>
<td>13-beam 1.35-GHz receiver</td>
</tr>
<tr>
<td><strong>Backend</strong></td>
<td>Pulsar Fast Fourier Transform Spectrometer (PFFTS)</td>
<td>Berkeley-Parkes-Swinburne Recorder (BPSR)</td>
</tr>
<tr>
<td><strong>Bandwidth</strong></td>
<td>300 MHz</td>
<td>340 MHz</td>
</tr>
<tr>
<td><strong>No. of channels</strong></td>
<td>512</td>
<td>1024</td>
</tr>
<tr>
<td><strong>Freq resolution</strong></td>
<td>0.58 MHz</td>
<td>0.39 MHz</td>
</tr>
<tr>
<td><strong>Time resolution</strong></td>
<td>54 $\mu$s</td>
<td>64 $\mu$s</td>
</tr>
<tr>
<td><strong>No. sky pointings</strong></td>
<td>~ 180,000</td>
<td>~ 43,000</td>
</tr>
<tr>
<td><strong>Data sizes</strong></td>
<td>~ 5 petabytes</td>
<td>~ 1 petabyte</td>
</tr>
</tbody>
</table>

All-sky high time & frequency resolution previously unachievable

→ Transient sky on timescale down to tens of $\mu$s

→ Higher freq. resolution for removing interstellar dispersion
A population of Fast Radio Burst at Cosmological Distances

- Four bursts discovered in high-lat part of HTRU (Thornton et al., Science, 2013)
- All at high galactic latitudes (|b| > 40 deg)
- DMs are very high: 500 – 1100 pc cm⁻³
- One very bright pulse allows further studies

### Table 1. Parameters for the four FRBs.

<table>
<thead>
<tr>
<th>FRB 110220</th>
<th>FRB 110627</th>
<th>FRB 110703</th>
<th>FRB 120127</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam right ascension (J2000)</td>
<td>22° 34'</td>
<td>21° 03'</td>
<td>23° 30'</td>
</tr>
<tr>
<td>Beam declination (J2000)</td>
<td>−12° 24'</td>
<td>−44° 44'</td>
<td>−02° 52'</td>
</tr>
<tr>
<td>Galactic latitude, b (°)</td>
<td>−54.7</td>
<td>−41.7</td>
<td>−59.0</td>
</tr>
<tr>
<td>Galactic longitude, l (°)</td>
<td>+50.8</td>
<td>+355.8</td>
<td>+81.0</td>
</tr>
<tr>
<td>DM (cm⁻³ pc)</td>
<td>944.38 ± 0.05</td>
<td>723.0 ± 0.3</td>
<td>1103.6 ± 0.7</td>
</tr>
<tr>
<td>$D_M$ (cm⁻³ pc)</td>
<td>910</td>
<td>677</td>
<td>1072</td>
</tr>
<tr>
<td>Redshift, z (DM_{host} = 100 cm⁻³ pc)</td>
<td>0.81</td>
<td>0.61</td>
<td>0.96</td>
</tr>
<tr>
<td>Co-moving distance, D (Gpc) at z</td>
<td>2.8</td>
<td>2.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Dispersion index, α</td>
<td>−2.003 ± 0.006</td>
<td>−2.000 ± 0.006</td>
<td>−</td>
</tr>
<tr>
<td>Scattering index, β</td>
<td>−4.0 ± 0.4</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Observed width at 1.3 GHz, W (ms)</td>
<td>5.6 ± 0.1</td>
<td>&lt;1.4</td>
<td>&lt;4.3</td>
</tr>
<tr>
<td>SNR</td>
<td>49</td>
<td>11</td>
<td>16</td>
</tr>
<tr>
<td>Minimum peak flux density, S (Jy)</td>
<td>1.3</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Fluence at 1.3 GHz, $F$ (Jy ms)</td>
<td>8.0</td>
<td>0.7</td>
<td>1.8</td>
</tr>
<tr>
<td>$S_D D^2$ (× 10¹² Jy kpc²)</td>
<td>10.2</td>
<td>1.9</td>
<td>5.1</td>
</tr>
<tr>
<td>Energy released, E (J)</td>
<td>$10^{33}$</td>
<td>$10^{31}$</td>
<td>$10^{31}$</td>
</tr>
</tbody>
</table>

Thornton et al. (2013)
A very bright burst allowing detailed studies

Thornton et al. (2013)

Note:

• Dispersion index: $2.003 \pm 0.006$
• Scattering index: $4.0 \pm 0.4$
• Inferred distance: $z = 0.81$
• Other bursts: $z = 0.45 – 0.96$
• Lorimer burst: $z = 0.3$
How to derive cosmological distances?

• Observed DM has various contributions: \( \text{DM}_{\text{obs}} = \text{DM}_{\text{MW}} + \text{DM}_{\text{IGM}} + \text{DM}_{\text{Host}} \)

• All but Keane-burst are at high Galactic latitudes, so that Milky Way contribution small

• DM from host is unlikely to be large (i.e. from central part) and also lever-arm effect, i.e. burst emitted at host at higher frequency than observed redshifted at Earth, hence, \( \text{DM}_{\text{Host}} \) also small

• Assuming fully ionised IGM, following Ioka (2003) & Ionue (2004), we derive

\[
z \approx \frac{\text{DM}_{\text{IGM}} (\text{pc cm}^{-3})}{1000}
\]

• Note that scattering is more difficult to interpret, as situation is more complex, since it depends on relative importance of turbulence in IGM and host, see e.g. Macquart & Koay (2013, arXiv:1308.4459)

• Ideally, we want to identify host to study the IGM! Unique opportunity!

• Ideally also in full polarisation to get also intergalactic magnetic fields!
What is the best strategy?

A number of severe uncertainties and unknowns:
- What is the exact position? Telescope position unlikely to be exact on target, hence observed flux density is likely to be underestimated.
- What are the spectra and luminosity functions? - What are they...?
- How severe is scattering, in particular at low frequencies?
- How reliable are these distances?

“Best-effort” estimates (for fluence of 3 Jy ms): \( R_{\text{FRB}} = 10000 \pm 6000 - 5000 \text{sky}^{-1} \text{day}^{-1} \)

Other estimates differ somewhat but are consistent (e.g. Hassall et al. 2013, arXiv:1308.4797)

At the moment, best consistent with ccSN but NS-NS merger also possible – something else??

New FoV instruments or surveys may detect a lot – depending on how severe scattering is!
(see e.g. Hassall et al. 2013 and Lorimer et al. 2013)

Consider also imaging surveys as an alternative (good localisation – poor time resolution)
How many FRBs will be detected?

Hassall al. (2013)

1 FRB/hour

1 FRB/hour
Radio Pulsar Searches in the future, already

Single Dishes
- Effelsberg
- Parkes
- Arecibo

Interferometers
- GMRT
- WSRT
- LOFAR

SKA
- SKA Mid
- SKA Low
- SKA Aperture Array
International LOFAR Telescope
Europe-wide radio interferometry array @ 10-240 MHz
Station in Effelsberg was the first of 9 international stations:
The Superterp
LOFAR core

Hassall – Slide by J. Hessels
LOFAR core

Slide by J. Hessels
LOFAR core

Slide by J. Hessels
LOFAR core

Slide by J. Hessels
Flexible Beam-forming

- As this is a sparse aperture array, you have several options:

Figure by van Leeuwen

Element beam  Stations beam(s)  Tied-array beam(s)
LOFAR Multi-beaming
High spatial and time resolution

Heald, Alexov & Hessels
LOFAR works, e.g. producing excellent polarisation data

These polarisation profiles from LOFAR are the best ever produced at these frequencies and, in several cases, the only polarisation profiles available below 200 MHz.

Slide by A. Noutsos
Team effort: LOFAR Pulsar Working Group

Jason Hessels (co-lead)  ASTRON / Universiteit van Amsterdam
Ben Stappers (co-lead)  University of Manchester
Anya Bilous  Radboud Universiteit Nijmegen
Thijs Coenen  Universiteit van Amsterdam
Sally Cooper  University of Manchester
Heino Falcke  Radboud Universiteit Nijmegen
Jean-Mathias Griessmeier  LPC2E/CNRS
Tom Hassall  University of Southampton
Aris Karastergiou  University of Oxford
Evan Keane  MPI für Radioastronomie
Vlad Kondratiev  ASTRON
Michael Kramer  MPI für Radioastronomie
Masaya Kuniyoshi  MPI für Radioastronomie
Joeri van Leeuwen  ASTRON / Universiteit van Amsterdam
Aris Noutsos  MPI für Radioastronomie
Maura Pilia  ASTRON
Maciej Serylak  LPC2E/CNRS
Charlotte Sobey  MPI für Radioastronomie
Sander ter Veen  Radboud Universiteit Nijmegen
Joris Verbiest  MPI für Radioastronomie
Patrick Weltevrede  University of Manchester
Kimon Zagkouris  University of Oxford
LOFAR Pulsar Survey

Great field-of-view

Great sensitivity

219 coherent beams
3 incoherent beams

LOTAAS - LOFAR Tied-Array All-Sky Survey

Slide by J. Hessels
Coherent “tied-array” beams

LOTAAS
Single
Pointing

222 beams (FoVs) at once

First SKA-like pulsar survey

Incoherent “station” beam

Slide by J. Hessels
LOTAAS
Sparse Sampling

Slide by J. Hessels
LOTAAS
Sparse
Sampling
Combined

Each sky position gets 3 observations

Slide by J. Hessels
Fast radio transient factories

Moon → Field-of-view

Parkes

0.6 sq. deg.

Big uncertainty:
Scattering at low frequencies?
LOTAAS will tell us!

Parkes → Moon

Current state-of-the-art

LOFAR
Field-of-view
60 sq. deg.

100x
In preparation for the radio telescope: the SKA!

- For pulsar science case see Kramer et al. (2004) & Cordes et al. (2004)
- For transient science case see Lazio et al. (2004)
Sensitivity comparison

![Graph showing Sensitivity comparison for different telescopes: SKA2, SKA1, MeerKAT, LOFAR, ASKAP, eVLA. The x-axis represents Frequency in MHz, and the y-axis represents Sensitivity in $\text{Aeff/Tsys} \text{m}^2\text{K}^{-1}$. The graph compares the performance of these telescopes across a range of frequencies.](image-url)
Survey speed comparison

Survey Speed: Sensitivity² * FoV A K² deg²

- SKA2
- SKA1
- LOFAR
- MeerKAT
- LOFAR
- ASKAP
- eVLA

Frequency MHz

Survey Speed: Sensitivity² * FoV A K² deg²

- SKA2
- SKA1
- LOFAR
- MeerKAT
- LOFAR
- ASKAP
- eVLA

The University of Manchester
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Max-Planck-Institut für Radioastronomie
Pulsar Discovery by Global Volunteer Computing


Already exploiting now:
- Neural networks (Eatough et al. 2010)
- Machine learning (Lee et al. 2013)
- Citizen Science (Knispel et al. 2010, 2013)

About 1 Exabyte per day!!!!
Synergies

- Currently, we have are limited in follow-up for identification of source and hosts
- ASKAP/MeerKAT/SKA and LSST will see the same hemisphere
- Immediate LSST follow-up of SKA triggers affected by seasons
- SKA-follow-up of LSST triggers can be quasi-instantaneous (see all-sky!)
- Currently, transient buffer for SKA too expensive but being considered
- Meanwhile, we improve current systems, e.g. Swinburne’s “Heimdall” system on Parkes
- Further collaborations: MoUs with gravitational wave community
- Upgrade existing telescopes, e.g. 100-m + LOFAR single station
Summary

- After 50 years of (fast) time-domain studies in the radio, entering a new era
- Lots of things are left to be discovered, incl. a whole population of cosmological bursts
- We still don’t know what they are...! But lots! One every 10 second! Stay tuned...!
- New instruments (now and in future) are a game changer - possible by digital revolution!
- We should try (and will be able) to measure polarisation also (magn. fields, coherence...)
- SKA and LSST will be an ideal combination

Lots to be done... lots of new phenomena to be discovered...

Btw, exciting SKA/LSST synergies also for studying gravity with binary pulsars!
- need GAIA and LSST data for improving model of Galactic acceleration
- but even better is the result from combining radio and optical data!
Optical-radio synergies: testing new gravity regimes

- Example: PSR J0348+0432 = first massive NS in relativistic orbit (Lynch et al. 2013)
- Combining VLT, Effelsberg, Arecibo & GBT data, new record mass measured:

\[ M = 2.01 \pm 0.04 \, M_\odot \]  (Antoniadis et al., Science, 2013)
Severe constrains on tensor-scalar gravity

- We can already rule out classes of tensor-scalar theories that were untestable before – much more possible with GAIA but in particular with LSST!

\[
\dot{P}_b = (-2.78 \pm 0.45) \times 10^{-13} \text{s s}^{-1}
\]

\[
\dot{P}_b / \dot{P}^\text{GR}_b = 1.05 \pm 0.17.
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