Pulsar Science with the SKA – An overview

Michael Kramer$^{1,2}$ & Ben Stappers$^2$ for the PSWG

$^1$ Max-Planck-Institut für Radioastronomie
$^2$ Jodrell Bank Centre for Astrophysics, University of Manchester
Pulsars...

...cosmic lighthouses
...almost Black Holes:
  mass of ~1.4 Solar Mass within 20km
...objects of extreme matter
  10x nuclear density
  $B \sim B_{cr} = 4.4 \times 10^{13}$ Gauss
  Voltage drops $\sim 10^{12}$ volts
  $F_{EM} = 10^{10-12} F_{gravity}$
  High-temperature & superfluid superconductor
...natural clocks with wide range of periods:

J1748-2446ad
  1.4 ms
  42,960 Rotations per Minute

J2144-3933
  8.5 s
  7

$\Rightarrow$ Lots of interesting precision physics...
Already today, we can do amazing measurements...

**Masses:**
- Masses of neutron stars: $m_1 = 1.24891(2) \, M_\odot$ and $m_2 = 1.33816(2) \, M_\odot$ (Kramer et al. in prep.)
- Mass of WD companions:
  - Shapiro: $0.204(2) \, M_\odot$ (Jacoby et al. 2005)
  - Optical: $0.181(7) \, M_\odot$ (Antoniadis et al. 2013)
- Mass of millisecond pulsar: $1.67(2) \, M_\odot$ (Freire et al. 2010)
- Main sequence star companion: $1.029(8) \, M_\odot$ (Freire et al. 2010)
- Mass of Jupiter and moons: $9.547921(2) \times 10^{-4} \, M_\odot$ (Champion et al. 2010)

**Spin parameters:**
- Period: $5.757451924362137(2) \, ms$ (Verbiest et al. 2008) = 2 atto seconds uncertainty!

**Orbital parameters:**
- Period: $0.102251562465(2) \, day$ (Kramer et al. in prep.)
- Eccentricity: $3.5 (1.1) \times 10^{-7}$ (Freire et al. 2012)

**Astrometry:**
- Distance: $157(1) \, pc$ (Verbiest et al. 2008)
- Proper motion: $140.915(1) \, mas/yr$ (Verbiest et al. 2008)

**GR tests:**
- Periastron advance: $4.226598(5) \, deg/yr$ (Weisberg et al. 2010)
- Shrinkage due to GW emission: $7.152 \pm 0.008 \, mm/day$ (Kramer et al. in prep)
- GR validity (obs/exp): $1.0000(5)$ (Kramer et al. in prep.)

But with the SKA...we can do so much more!!
So far, pulsar science hasn’t done badly...

• Pulsar astrophysics has a quite impressive track record of discoveries

• Large range of applications in the widest area of physics and astrophysics from smallest (=solid states physics) to largest scales (=grav. physics)

• Don’t think that we have enough! ... quite the opposite!

• The SKA is a superb instrument for pulsar research:
  - large collecting area
  - large fractional bandwidth
  - large field-of-view
  - multi-beaming capabilities

  \[
  \begin{align*}
  & \text{Never have enough of that..!} \\
  & \text{Monitoring and searching with} \\
  & \text{excellent cadence & survey speed}
  \end{align*}
  \]

• We have high expectations based on previous and recent experience
Key Science and more...

- Key Science ("Gravity with pulsars and BHs") described in Kramer et al. (2004)
- Key Science capabilities enable a wide range of further exciting science, as described in Cordes et al. (2004) and other chapters:
  
  Cosmic census for pulsars:
  - Galactic population of radio emitting neutron stars (pulsars, magnetars etc.)
  - Galactic centre pulsars
  - Globular clusters & external galaxies

  Fundamental physics:
  - Tests of theories of gravity, incl. BH properties
  - Detection and study of gravitational waves, GW astronomy
  - Equation-of-state of super-dense matter, structure of neutron stars

  Relativistic plasma physics: Pulsar magnetospheres, emission physics.

  Mapping the Milky Way: interstellar medium, Galactic magnetic field.

  Properties of the intergalactic medium: giant pulses from extragalactic pulsars.

  Core-collapse supernova, formation of neutron stars, birth properties.
A simple recipe

1. Find them
2. Time them
3. VLBI them

In other words: Discovering is not enough.

To extract science, timing (follow-up) observations of all discovered pulsars are needed.
On-going Radio Pulsar Surveys

- HTRU-North
- AO 327 MHz drift scan
- LOFAR
- GBNCC
- HTRU-South
- PALFA
- SPAN512
- Galactic Centre – various
- PMPS re-analysis E@H
- GBT350
Lots of discoveries since SKA Science Book: “We’ve been busy...”

• Currently, more than 2,300 pulsars, and nearly 300 millisecond pulsars
• Since 2004 Science Book, nearly twice as many normal pulsars and three times as many millisecond pulsars (digital signal processing!)
Discoveries lead to excellent science!

- 1970-1975: Year
- 0.1-0.9: Cumulative Distribution
- 1970-2010: Year

Key Discoveries:
- Double Pulsar
- Fastest MSP!
- RRATs
- Missing-link pulsar
- Sub-100ns timing
- "Lorimer Burst"
- Intermittent pulsars
- Galactic centre Magnetar J0348+0432
- 100th FERMI Pulsar
- 1st Blind-search radio magnetar
- Thornton et al. Bursts
- 2-M\(\odot\) Pulsar
- 1st Pulsars via AI and Volunteer Computing
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Discoveries lead to excellent science!

- Exciting science ranging from solid-state physics to testing gravity.
- Obviously, we do need an updated science book.
- Nevertheless, expectation confirmed: previously proposed science reinforced!
• We can expect to find about 30,000 active (visible) pulsars
• Among those will be about 2000 millisecond pulsars
• A dramatic increase in the number of known sources!

“...but that’s only the beginning!”
Cosmic census with the SKA

With SKA’s collecting area and increase in survey speed:

(Kramer et al. 2004, Cordes et al. 2004, Smits et al. 2008)

- ~30,000 normal pulsars
- ~2,000 millisecond pulsars
- ~100 relativistic binaries
- first pulsars in Galactic Centre
- first extragalactic pulsars

➔ rare and exotic pulsars and binary systems: including PSR-BH systems!
➔ lots of pulsars for GW astronomy
➔ enabling key science but also a large range of more physics & astrophysics
The benefits of the SKA and its pathfinders

Important: Sensitivity, FoV/Survey speed, frequency range

- timing precision, ability to find rare systems, cadence, time on sky, f-leverage

<table>
<thead>
<tr>
<th></th>
<th>JVLA</th>
<th>MeerKAT</th>
<th>SKA1-mid</th>
<th>ASKAP</th>
<th>SKA1-survey</th>
<th>LOFAR-NL</th>
<th>SKA1-low</th>
</tr>
</thead>
<tbody>
<tr>
<td>A_eff/T_sys</td>
<td>m²/K</td>
<td>265</td>
<td>321</td>
<td>1630</td>
<td>65</td>
<td>391</td>
<td>61</td>
</tr>
<tr>
<td>Survey FoV</td>
<td>deg²</td>
<td>0.14</td>
<td>0.48</td>
<td>0.39</td>
<td>30</td>
<td>18</td>
<td>6</td>
</tr>
<tr>
<td>Survey Speed FoM</td>
<td>deg² m⁴/K²</td>
<td>0.98 x 10⁴</td>
<td>5.0 x 10⁴</td>
<td>1.0 x 10⁶</td>
<td>1.3 x 10⁵</td>
<td>2.8 x 10⁶</td>
<td>2.2 x 10⁴</td>
</tr>
<tr>
<td>Resolution</td>
<td>arcsec</td>
<td>1.4</td>
<td>11</td>
<td>0.22</td>
<td>7</td>
<td>0.9</td>
<td>5</td>
</tr>
</tbody>
</table>

| A_eff/T_sys:     | 6xJVLA | 6xASKAP | 16xLOFAR |
| Survey Speed:    | 100x    | 22xASKAP | 270xLOFAR |
|                  | 280xJVLA |
The challenges of “non-imaging processing”

- Blind survey over the FoV requires beam forming, $N_{\text{beam}} \sim \left( \frac{b_{\text{max}}}{D} \right)^2$
- Baseline design: $N_{\text{beam}}(1\text{deg}^2@1\text{GHz})=2300$, $N_{\text{beam, max}} = 4000$
- Each beam has to be processed - on the fly!
- Essentially: de-dispersion + Fourier transform + RFI excision + Candidate selection
- No-human involvement: machine learning & artificial intelligence
- Big challenge: acceleration search for unknown orbits: $N_{\text{ops}} \sim T_{\text{obs}}^3$

Note: We cannot trade sensitivity for observing time!
Reason: For searching, computing; for timing, science!
Phase I will already be an excellent search machine

- Excellent lessons from SKA Pathfinders, in particular LOFAR! (see Jason’s talk)
- Full Phase-II collecting area unlikely to be utilized for foreseeable future
- We can find nearly 50% of all pulsars with Phase I already – in combination of SKA-low and SKA-mid:

SKA1_Low, 1hr integrations

van Leeuwen (priv. comm.)
Phase I will already be an excellent search machine

- Excellent lessons from SKA Pathfinders, in particular LOFAR!
- Full Phase-II collecting area unlikely to be utilized for searching (dep. on config.)
- We can find nearly 50% of all pulsars with Phase I already – in combination of SKA-low and SKA-mid:

Note:
- Phase I will be great for searching – but we also need to use SKA-low
- Search frequency needs to be flexible (e.g. inner Galaxy vs. higher lat.)
- We need to time all of these pulsars... at least for a while...
Science with pulsars - as objects or tools

Our science topics have not really changed since 2004 – only reaffirmed:

✓ Tests of gravity with pulsars: see talk by Lijing Shao
✓ Radio pulsars in the Galactic Centre: see talk by Ralph Eatough
✓ Gravitational wave astronomy: see talk by Gemma Janssen
✓ Cosmic census of radio emitting neutron stars - now including also: intermittent pulsars, RRATs, magnetars: see talk by Evan Keane
✓ Understanding the neutron star population: see talk by Vicky Kaspi
✓ Pulsars in Globular Clusters: see talk by Jason Hessels
✓ Properties of super-dense matter: see talk by Renxin Xu
✓ Understanding the pulsar magnetospheres: see talk by Aris Karastergiou
✓ Galactic structure (incl. ISM & magnetic field): talk by Jinlin Han
✓ Pulsar Wind Nebulae: see talk by Yosi Gelfand
Thanks to a large number of colleagues...

Gravity tests: Antoniadis, Bailes, Cognard, Deller, Freire, Hessels, Janssen, Kramer, Kunz, Lämmerzahl, Perlick, Possenti, Ransom, Shao, Stairs, Stappers, Theureau, van Straten, Wex

Gravitational wave astronomy: Allen, Bassa, Champion, Cognard, Deller, Demorest, Hobbs, Janssen, Keith, Kramer, Lee, McLaughlin, Ransom, Shao, Stairs, Stappers, Theureau, van Straten, Verbiest, Wex

Cosmic Census: Bailes, Burgay, Champion, Cognard, Cordes, Chatterjee, Eatough, Hessels, Janssen, Johnston, Karastergiou, Keane, Keith, Kramer, Lee, Possenti, Ransom, Stappers, Theureau, Torne, van Leeuwen

EOS – NS structure: Andersson, Antoniadis, Breton, Buchner, Dai, Demorest, Freire, Hessels, Possenti, Ransom, Stairs, Watts, Xu

NS population: Breton, Deller, Kaspi, Keane, Kramer, Possenti, Tauris

Galactic structure & ISM: Cordes, Deller, Demorest, Han, Hessels, Gaensler, Imai, Karastergiou, Keith, Lazio, Lee, Noutsos, Schnitzeler, van Straten, Sobey

External galaxies: Breton, Burgay, Cordes, Hessels, Stappers

Pulsar Magnetospheres: Breton, Han, Johnston, Hessels, Karastergiou, Keane, Kramer, McLaughlin, Possenti, van Leeuwen, Weltevrede, Sobey

Synergies: Antoniadis, Bassa, Bogdanov, Guillemot, Kramer, Mignani, Torne

Pulsars in Globular Clusters: Bailes, Bassa, Freire, Hessels, Lynch, Possenti, Ransom, Stairs

Pulsar Wind Nebula: Breton, Gelfand, Hessels, Ng, Pellizzoni, Possenti, Roberts, Stappers

Galactic Centre Pulsars: Eatough, Lazio, Chatterjee, Cordes, Demorest, Kramer, Lazio, Ransom, Wex
Thanks to a large number of colleagues... also from US!

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Conclusions

• The SKA will be a superb tool for fundamental physics and many astrophysical problems
• With pulsars alone, the SKA will probe science from solid states physics to gravitation
• The SKA will provide the best strong-field tests of GR & complement GW detectors
• Properties of black holes will be determined: cosmic censorship, no-hair theorem
• Low-frequency gravitational waves will be detected and used for:
  - GW astronomy, cosmology & galaxy evolution, graviton properties
• Science essentially still the same as proposed in 2004 KSP chapter – but even better!
  See the following talks!

• There will be superb synergies with GAIA, ELTs, LSST, CTA, AdvLIGO, LISA etc.
• The SKA configuration is crucial – SKA-low would be extremely useful together with SKA-mid

From fundamental physics to astrophysics.
It’s going to be exciting.