Simultaneous XMM-Newton Radio Observations of the Mode-switching Radio Pulsar PSR B1822-09

Wim Hermsen$^{1,2}$

Collaborators:
J.W.T. Hessels$^{3,2}$, L. Kuiper$^1$, J. van Leeuwen$^{3,2}$, D. Mitra$^4$, J.M. Rankin$^{2,5}$, B. Stappers$^6$, G.A.E. Wright$^7$ & R. Basu$^4$

1 SRON Netherlands Institute for Space Research
2 Astronomical Institute "Anton Pannekoek", University of Amsterdam
3 ASTRON Netherlands Institute for Radio Astronomy
4 National Centre for Radio Astrophysics, Ganeshkhind, Pune, India
5 Physics Department, University of Vermont, Burlington, USA
6 Jodrell Bank Center for Astrophysics, Manchester, UK
7 Astronomy Centre, University of Sussex, Falmer, Brighton, UK
Outline

  (Hermsen et al. 2013, Science 339, 436)

• Simultaneous radio and X-ray observations of PSR B1822-09: results

• Conclusions / Dilemma’s
PSR B0943+10; 6x6 hrs of simultaneous XMM-Newton X-ray and GMRT/LOFAR radio observations

Characteristics of PSR B0943+10

- $P = 1.10$ s
- $\dot{P} = 3.5 \times 10^{-15}$
- $E = 1.0 \times 10^{32}$ ergs s$^{-1}$
- $B_p = 2 \times 10^{12}$ G
- $T = 5.0 \times 10^6$ yr
- Nearly aligned rotator

- mode switching between radio B(right) and Q(quiet) modes
XMM-Newton PN, Maximum-Likelihood Maps, 0.2-10 keV

B-mode windows

- $t_{\text{eff}} = 39.7$ ks
- $9.9\sigma$ detection
- $174 \pm 36$ cnts
- $(0.44 \pm 0.07) \times 10^{-2}$ cnts/s

Q-mode windows

- $t_{\text{eff}} = 43.5$ ks
- $20\sigma$ detection
- $470 \pm 33$ cnts
- $(1.08 \pm 0.08) \times 10^{-2}$ cnts/s

Discovery of correlated Radio – X-ray mode changes
Anti correlation!
Discovery of X-ray pulsation only in radio Q mode intervals!

XMM-Newton
EPIC PN + MOS-1
+ MOS-2

Difference between X-ray emissions in radio B and Q mode is addition of a pulsed X-ray component in Q mode!

X-ray pulse aligned with radio main pulse with precursor

W.Hermsen, Physics of Neutron Stars 2014, St. Petersburg
Pulsed fractions

Pulsed fractions of PSR B093+10 as a function of energy, defined as the ratio of the flux in the pulse profile over the total flux of the point source measured in the sky maps. Errors are 1σ.

<table>
<thead>
<tr>
<th>Energy interval keV</th>
<th>Pulsed fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2 - 0.5</td>
<td>0.10 ± 0.15</td>
</tr>
<tr>
<td>0.5 - 0.8</td>
<td>0.44 ± 0.16</td>
</tr>
<tr>
<td>0.8 - 1.3</td>
<td>0.62 ± 0.14</td>
</tr>
<tr>
<td>1.3 - 2.0</td>
<td>0.60 ± 0.17</td>
</tr>
<tr>
<td>2.0 - 10</td>
<td>0.72 ± 0.53</td>
</tr>
</tbody>
</table>
Pulsed emission X-ray spectrum of PSR B0943+10: radio Q-mode

- **Best fit**: BB; $\chi^2/\nu = 1.14/3$, ~78%
- $N_H = 4.3 \times 10^{20}$ cm$^{-2}$ (fixed)
- BB: $kT = 0.319 \pm 0.012$ keV
- $F_{BB} (0.5-8 \text{ keV}) = (7.8 \pm 1.6) \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ (unabsorbed)
- $R_{\text{hot spot}} \approx 18$ m ($d = 630$ pc)

**PL fit**; $\chi^2/\nu = 9.50/3$, ~2.3%
Conclusions on X-ray spectral characteristics

- Radio B mode: unpulsed, non-thermal emission (index and normalization within $1\sigma$ the same as for power-law component in Q mode)

- Radio Q mode: same unpulsed non-thermal emission plus pulsed thermal emission
Many unanswered questions, dilemma's:

- The polar cap region is viewed continuously: how to produce a 100%-pulsed thermal component in the Q mode?
- How to switch off a thermal X-ray component in the B mode while the radio emission becomes bright and ordered.

etc., etc, ......
New X-ray and radio campaign on PSR B1822-09

Characteristics:

<table>
<thead>
<tr>
<th>PSR B0943+10</th>
<th>PSR B1822-09</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P = 1.10 \text{ s}$</td>
<td>$0.77 \text{ s}$</td>
</tr>
<tr>
<td>$\dot{P} = 3.5 \times 10^{-15}$</td>
<td>$5.2 \times 10^{-14}$</td>
</tr>
<tr>
<td>$E = 1.0 \times 10^{32} \text{ erg s}^{-1}$</td>
<td>$4.5 \times 10^{33} \text{ erg s}^{-1}$</td>
</tr>
<tr>
<td>$B_p = 2.0 \times 10^{12} \text{ G}$</td>
<td>$6.4 \times 10^{12} \text{ G}$</td>
</tr>
<tr>
<td>$T = 5.0 \times 10^6 \text{ yr}$</td>
<td>$2.3 \times 10^5 \text{ yr}$</td>
</tr>
</tbody>
</table>

- nearly **aligned** rotator
- nearly **orthogonal** rotator

(but, Malov & Nikitina 2011, 2013: aligned rotator)

- Both pulsars mode switching between radio B(right) and Q(quiet) mode
PSR B1822-09 @ 624 MHz (GMRT)

Mode switching

1: Precursor
2: Main pulse
3: Interpulse

Typical mode durations less than 5 minutes
**XMM-Newton** observation times (ks) in September, October 2013, and March 2014

<table>
<thead>
<tr>
<th>Date/CCDs</th>
<th>10/09 2013</th>
<th>18/09 2013</th>
<th>22/09 2013</th>
<th>28/9 2013</th>
<th>30/09 2013</th>
<th>06/10 2013</th>
<th>10/03 2014</th>
<th>12/03 2014</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>PN</td>
<td>23.1</td>
<td>21.1</td>
<td>24.8</td>
<td>21.1</td>
<td>27.9</td>
<td>21.1</td>
<td>21.1</td>
<td>34.1</td>
<td>Large Window</td>
</tr>
<tr>
<td>MOS-1</td>
<td>24.8</td>
<td>22.8</td>
<td>26.5</td>
<td>22.8</td>
<td>29.6</td>
<td>22.8</td>
<td>22.8</td>
<td>35.8</td>
<td>Small Window</td>
</tr>
<tr>
<td>MOS-2</td>
<td>24.8</td>
<td>22.8</td>
<td>26.5</td>
<td>22.8</td>
<td>29.6</td>
<td>22.8</td>
<td>22.8</td>
<td>35.8</td>
<td>Small Window</td>
</tr>
</tbody>
</table>

Simultaneous radio observations with the **WSRT, Lovell and GMRT**

Total XMM-Newton    | PN       | 194.3 ks   | MOS-1    | 209.3 ks   | MOS-2    | 209.3 ks   |
---------------------|----------|------------|----------|------------|----------|------------|

X-ray spatial analysis of skymaps

- **Maximum Likelihood Analysis**
- Two sources are detected separated by 5.3″±0.5″
- A soft-spectrum source at the position of PSR J1822-09, dominating below 1.4 keV
- A hard-spectrum source dominating above 1.4 keV

W.Hermsen, Physics of Neutron Stars 2014, St. Petersburg
Example Maximum Likelihood maps PN detector, Runs 1-3

At position PSR B1822-09

31.5σ 751±37 cnts

Location contours

6.4σ 84±17 cnts

Shifted position

0.3 – 2 keV

2-10 keV

W. Hermsen, Physics of Neutron Stars 2014, St. Petersburg
Raw skymaps for MOS1+2, Runs 1-6

Total number of counts
PSR1822-09
Runs 1-8
PN 2144 cnts
MOS1+2 810 cnts
X-ray timing analysis  (Runs 1-8, PN+MOS1+2)

Detection of X-ray pulsation in energy band 0.4-1.4 keV

**Phase folding with ephemeris from Jodrell Bank**

- Broad sinusoidal X-ray pulse shifted by ~0.07 in phase with respect to radio main pulse (0.0)
- No indication for X-ray pulse from radio interpulse
- Pulsed fraction ~35%

9.8 σ detection significance
X-ray timing analysis

Profiles in differential energy bands: pulse detections only between 0.4 and 1.4 keV ($z_1^2$ statistic)

Dashed profiles are fits with profile shape for integral energy band 0.4-1.4 keV at fixed phase.
X-ray mode switching?
PSR B1822-09, 5.55 hrs observing with the WSRT

S/N of detection in bins of 10 s
X-ray mode switching? Preliminary result for runs 1-6

Q-mode 85.5 ks and B-mode 50.4 ks

- Skymap analysis with Maximum Likelihood Method of count maps separately for PN and MOS1+2 detectors and $\Delta E$:
  - 0.15-0.4 keV & 0.4-1.4 keV fitting 1 source (PSR B1822-09)
  - 1.4-10 keV fitting 2 sources
**X-ray mode switching?** Preliminary result for **runs 1-6**

Q-mode 85.5 ks and B-mode 50.4 ks

Count rates total emission PSR B1822-09

<table>
<thead>
<tr>
<th>ΔE</th>
<th>0.15 – 0.4 keV</th>
<th>0.4 – 1.4 keV</th>
<th>1.4 – 10 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>No mode selection</td>
<td>(2.52±0.21)x10^{-3}</td>
<td>(8.97±0.34)x10^{-3}</td>
<td>(0.73±0.27)x10^{-3}</td>
</tr>
<tr>
<td>B-mode</td>
<td>(2.67±0.35)x10^{-3}</td>
<td>(7.98±0.53)x10^{-3}</td>
<td>(0.96±0.44)x10^{-3}</td>
</tr>
<tr>
<td>Q-mode</td>
<td>(2.41±0.27)x10^{-3}</td>
<td>(9.60±0.44)x10^{-3}</td>
<td>(0.57±0.34)x10^{-3}</td>
</tr>
<tr>
<td>Δ B-Q modes</td>
<td>0.6 σ</td>
<td>-2.4 σ</td>
<td>0.7 σ</td>
</tr>
</tbody>
</table>

→ only 2.4 σ hint for X-ray mode switching in 0.4-1.4 keV band, which contains pulsed signal
X-ray mode switching? Preliminary result for runs 1-6

Q-mode 85.5 ks and B-mode 50.4 ks

- Timing/phase resolved imaging for 10 phase bins

Upper figure shows source count rates: broken lines B mode, solid line Q mode

Lower figure: count rate difference (Q-B) as a function of phase

KS-test: 30% chance probability that both distributions are drawn from same parent distribution
X-ray mode switching? Preliminary result for runs 1-6

Q-mode 85.5 ks and B-mode 50.4 ks

- Timing/phase resolved imaging for 10 phase bins

Upper figure shows source count rates: broken lines B mode, solid line Q mode

No significant evidence for mode switching

Lower figure: count rate difference (Q-B) as a function of phase

KS-test: 30% chance probability that both distributions are drawn from same parent distribution
Spectral analysis

- Distance PSR B1822-09:
  Upper limit $1.9$ kpc (Johnston et al. 2001),
  often quoted $d \sim 1$ kpc (e.g. Zhou et al. 2005).

- $N_H$ at $\sim 1.9$ kpc is $\sim 3 \times 10^{21}$ cm$^{-2}$

- $N_H$ is in initial analysis treated as free parameter
Pulsed emission X-ray spectrum of PSR B1822-09: ‘absorbed’

- **BB fit**: \( \chi^2_v = 1.14 \) (d.o.f. 6)
  - \( N_H = (2.03^{+0.35}_{-0.30}) \times 10^{21} \) cm\(^{-2}\)
  - \( \text{BB norm} = 0.0047 \pm 0.0007 \)
  - \( kT = 0.138^{+0.003}_{-0.004} \) keV

- **PL fit**: \( \chi^2_v = 1.11 \) (d.o.f. 6)
  - \( N_H = (9.28^{+0.36}_{-0.30}) \times 10^{21} \) cm\(^{-2}\)
  - \( \alpha = (1.85 \pm 0.28) \times 10^{-5} \) ph cm\(^{-2}\) keV\(^{-1}\) at 1 keV
  - \( \Gamma = -9.5^{+0.5}_{-0.4} \)
Pulsed emission X-ray spectrum of PSR B1822-09 (‘unabsorbed’)
Total emission X-ray spectrum of PSR B1822-09 (‘unabsorbed’)

- PL fit: $\chi^2_v = 1.65$ (d.o.f. 32)
  - $\sim 1\%$ prob.
  - $N_H = (4.15 \pm 0.05) \times 10^{21} \text{ cm}^{-2}$
  - $\Gamma = -6.77 \pm 0.07$
  - BB fit : $\chi^2_v = 1.60$ (d.o.f. 32)
    - $\sim 1\% - 2\%$ prob.

- BB+PL fit: $\chi^2_v = 1.43$ (d.o.f. 30)
  - $\sim 7.5\%$ prob.
  - $N_H = (2.85 \pm 0.08) \times 10^{21} \text{ cm}^{-2}$
  - $BB_{\text{norm}} = 0.093 \pm 0.010$
  - $kT = 0.098 \pm 0.002 \text{ keV}$
  - $R_{\text{hot spot}} \approx 948 \text{ m (d = 1 kpc)}$
  - $\alpha = (1.85 \pm 0.28) \times 10^{-5} \text{ ph cm}^{-2} \text{ keV}^{-1}$ at 1 keV
  - $\Gamma = -5.76 \pm 0.15$
JOINT FIT TO TOTAL AND PULSED SPECTRA OF PSR B1822-09

Assuming that:
• pulsed emission is a BB and equals BB component in total spectrum.
• Unpulsed emission has a PL shape

• BB+PL fit: $\chi^2_v = 1.40$ (d.o.f. 39) ~5% prob.
• $N_H = (3.39 \pm 0.08) \times 10^{21}$ cm$^{-2}$
• $BB_{norm} = 0.0345 \pm 0.0046$
• $kT = 0.112 \pm 0.002$ keV
• $R_{hot \; spot} \approx 578$ m ($d = 1$ kpc)
• $\alpha = (5.0 \pm 0.4) \times 10^{-6}$ ph cm$^{-2}$ keV$^{-1}$ at 1 keV
• $\Gamma = -6.62 \pm 0.13$
Conclusions / Dilemma’s

• PSR B1822-09 has been detected with XMM-Newton with a pulsed fraction of \(~35\%\) in the energy band \(0.4-1.4\) keV

• The pulse profile is sinusoidal; maximum within 0.1 phase from the peak of the radio main pulse; no pulse detected at the phase of the weak radio inter pulse.

• There is no significant evidence for simultaneous X-ray-radio mode-switching by PSR B1822-09. What causes this difference with PSR B0943+10?

• The spectrum of the total emission is best fitted with a thermal BB-component plus a non-thermal PL component.

• The spectrum of the pulsed component is best fitted with a thermal component, consistent with a heated polar cap passing through our line-of-side for an orthogonal rotator. But, what about a non-thermal unpulsed component?

• The X-ray-radio characteristics of PSR B1822-09 do not shed more light on the interpretation of the X-ray/radio characteristics of PSR B0943+10

Etc .etc..... Many open questions
Thank you for listening!