Simultaneous X-ray and radio mode switching: Local and/or magnetospheric phenomenon?

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Outline

- **Radio-mode switching; PSR B0943+10, B1822-09, B0823+26**

- **Synchronous X-ray and radio-mode switching in PSR B0943+10.**

- **Simultaneous X-ray and radio observations of the radio-mode-switching pulsar PSR B1822-09.**

- **Discovery of synchronous X-ray & Radio moding of PSR B0823+26.**

- Comparison results on PSRs B0943+10, B1822-09 & B0823+26
It began with a question in 2006......

PSR B0943+10: radio-mode switching

Q-to-B-Mode Transitions in B0943+10
Arecibo 327-MHz observations in 2003

Profiles are 480-pulse averages

Suleymanova & Izvekova 1984
Four radio-X-ray campaigns on three mode switching pulsars 2011 - 2017

**X-rays:** XMM

**Radio:**
- GMRT
- LOFAR
- WSRT
- Lovell
- Arecibo
- LWA
Radio-X-ray campaigns on three radio-mode switching pulsars 2011 - 2017

<table>
<thead>
<tr>
<th></th>
<th>PSR B0943+10</th>
<th>PSR B1822-09</th>
<th>PSR B0823+26</th>
</tr>
</thead>
<tbody>
<tr>
<td>P [s]</td>
<td>1.10</td>
<td>0.77</td>
<td>0.53</td>
</tr>
<tr>
<td>P-dot</td>
<td>$3.5 \times 10^{-15}$</td>
<td>$5.2 \times 10^{-14}$</td>
<td>$1.7 \times 10^{-15}$</td>
</tr>
<tr>
<td>E-dot [erg s$^{-1}$]</td>
<td>$1.0 \times 10^{32}$</td>
<td>$4.5 \times 10^{33}$</td>
<td>$4.5 \times 10^{32}$</td>
</tr>
<tr>
<td>$B_p$ [G]</td>
<td>$2.0 \times 10^{12}$</td>
<td>$6.4 \times 10^{12}$</td>
<td>$9.6 \times 10^{11}$</td>
</tr>
<tr>
<td>Characteristic age [yr]</td>
<td>$5.0 \times 10^{6}$</td>
<td>$2.3 \times 10^{5}$</td>
<td>$4.9 \times 10^{6}$</td>
</tr>
<tr>
<td>B field / rotation axis</td>
<td>‘aligned’</td>
<td>‘orthogonal’</td>
<td>‘orthogonal’</td>
</tr>
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</table>
Radio-mode switching a local or global phenomenon?

**Observational Evidence** for Rapid, Global, Magnetospheric Changes:

- Mode switching and correlated $\dot{v}$ changes for PSR B1931+2421
  
  (Kramer et al. 2006, Science 312, 549)
Radio-mode switching a local or global phenomenon?

Observational Evidence for Rapid, Global, Magnetospheric Changes:

- Mode switching and correlated $\nu$ changes for PSR B1931+2421
  (Kramer et al. 2006, Science 312, 549)

- Mode changing, nulling, profile-shape changes likely due to change in magnetospheric particle current flow (Lyne et al. 2010, Science 329, 408)

- Similar behaviour for PSR J1841-0500 and J1832+0029
  (Camilo et al. 2012; Lorimer et al. 2012)

- Two more long-term intermittent pulsars, PSRs J1910+0517, J1929+1357, with PSR J1929+1357 showing $\nu$ proportional to duty cycle (Lyne et al. 2017, Ap.J. 834, 72)

- Theoretical discussions on global quasi-stable magnetospheric states
Radio-mode switching a local or global phenomenon?

**Local phenomenon, Inner Acceleration Region:**
- Three modes of pulsar inner gap (Zhang et al. 1997)
- Partially Screened Gap model (Gil, Melikidze, Zhang, 2006; Szary, Melikidze, Gil, 2015)

**Accretion:**
- Interstellar medium
- Fallback debris

**Can X-ray observations help?**
**PSR B0943+10**: radio-mode switching Main Pulse and Precursor mode durations typically **hour(s)**

Hermsen et al. 2013

"Magnetospheres of Neutron Stars and Black Holes", GSFC, June 2019
Discovery of synchronous radio / X-ray mode switching

PSR B0943+10

Anti-correlated radio and X-ray modulation!

Single X-ray pulse aligned with radio main pulse

Hermsen et al. 2013, Science 339, 436

"Magnetospheres of Neutron Stars and Black Holes", GSFC, June 2019
Discovery of synchronous radio / X-ray mode switching

Hermsen et al. 2013, Science 339, 436


**PSR B0943+10**: near alignment

X-ray pulsed emission is thermal: $kT \sim 3.4$ MK, $R_{BB} \sim 21$ m

X-ray unpulsed emission non-thermal: PL photon index $\sim -2.5$
Discovery of synchronous radio / X-ray mode switching


Hermsen et al. 2013, Science 339, 436

PSR B0943+10: near alignment

Magnetized hydrogen atmosphere model
PSR B1822-09: radio moding Precursor, Main and Interpulse mode durations typically minutes

Hermsen et al. 2017

Precursor switches in correlation with Main pulse
Interpulse switches in anti-correlation with Main pulse
PSR B1822-09: radio moding Precursor, Main and Interpulse mode durations typically minutes

Hermsen et al. 2017

GMRT

B

Q

NO X-ray mode changing

Single X-ray pulse lags radio pulse

PSR B1822-09: orthogonal rotator

"Magnetospheres of Neutron Stars and Black Holes", GSFC, June 2019
**PSR B1822-09**: radio moding Precursor, Main and Interpulse mode durations typically minutes

X-ray total emission is thermal:

- $kT_1 \approx 1.0$ MK \quad $R_{BB} \approx 2$ km
- $kT_2 \approx 2.2$ MK \quad $R_{BB} \approx 100$ m

Hot component: pulsed emission

Cool component: from NS surface

High pulsed fraction $\sim 60\%$ @ 1keV:
- One X-ray MP + one weaker X-ray IP
- Magnetic beaming involved?
**PSR B0823+26**: radio moding Postcursor, Main and Interpulse mode durations typically **hours / days**

Main pulse, Interpulse and Postcursor all show correlated switch

Also OFF state: nulling

Sobey et al. 2015; LOFAR
PSR B0823+26: radio moding Postcursor, Main and Interpulse mode durations typically hours / days

XMM-Newton

Correlated radio / X-ray moding!

Sobey et al. 2015; LOFAR

"Magnetospheres of Neutron Stars and Black Holes", GSFC, June 2019
PSR B0823+26: radio moding Postcursor, Main and Interpulse mode durations typically hours / days

Near orthogonal rotator

Single broad X-ray pulse

X-ray pulse lags radio pulse

Pulsed fraction very high ~80%
**PSR B0823+26**: radio moding Postcursor, Main and Interpulse mode durations typically *hours / days*

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**XMM-Newton**

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**X-ray total and pulsed emissions thermal:**

\[ kT_1 \approx 1.4 \text{ MK}, \quad R_{BB} \approx 77 \text{ m} \]
\[ kT_2 \approx 4.3 \text{ MK}, \quad R_{BB} \approx 8.5 \text{ m} \]
PSR B0823+26: spectral analysis for B mode

Magnetized partially ionized hydrogen atmosphere model Ho (2014)

However, angle between rotation axis and line-of-sight direction ~66°, while radio-derived value is ~84: inconsistency?
PSR B0823+26: X-ray count rates 0.2-2 keV in ~1 hr bins

In skymap 4.6 σ!
PSR B0823+26
April 24, 7.5 hrs of Q-mode observations plus short ~6 minutes ‘B-like’.

GMRT at 339.3 MHz

In skymap 4.5 $\sigma$ in interval of 21 minutes

“Magnetospheres of Neutron Stars and Black Holes”, GSFC, June 2019
PSR B1823+26 radio-burst structure

Q-to-B is sudden................but B-to-Q is not

PSR B0943+10 & B1822-09 both transitions are sudden
PSR B1823+26 radio-burst structure

Q mode exhibits for >90% short nulls with occasional pulses/bursts
B mode ~ 1-2% short nulls  
(Basu & Mitra 2019; Rankin & Olszanski)

PSR B0943+10 & B1822-09 do not show such short nulls
PSR B1823+26 radio-burst structure

Sudden appearance of strong bursts, self-organized criticality?

Accretion from interstellar medium?
A clue (Wright, Pharos meeting 2019): ‘revived’ magnetar XTE J1810-197

- Burst into activity December 2018
- Quiescent and Bright modes
- Sudden onset of burst in radio and X rays

Timescale: 10 years

Gotthelf et al. 2019
Similar profiles

- Single-peak X-ray pulse
- X-peak follows radio peak
- Pre- and post-cursors

**XTE J1810-197**

**PSR B0823+26**

Hermsen et al. 2018

Gotthelf et al. 2019
Post- and Pre-cursor of XTE J1810-197

- Precursor migrates to postcursor over 50 days!

Lovell
1.52 GHz

Levin et al. 2019
Same pattern on different timescales

Pulsar $P = 0.53 \text{ s}$

Magnetar $P = 5.54 \text{ s}$

$B \sim 10^{12} \text{ G}$

$B \sim 2 \times 10^{14} \text{ G}$

But spindown loss rate $\sim 5 \times 10^{32} \text{ erg/s} - \text{ same for both}$
Summary

- PSR B0943+10, B1822-09 and B0823+26 exhibit very different radio (moding) characteristics

- PSR B0943+10 shows anti-correlated X-ray / radio mode switching of a thermal pulse and a non-thermal unpulsed component.

- PSR B1822-09 shows no X-ray mode switching

- PSR B0823+26 shows correlated X-ray / radio mode switching with a two-temperatures thermal pulse

→ Simultaneous X-ray and radio mode switching: Local and/or magnetospheric phenomenon?
Thank you for listening!