PULSARS

X-ray emission properties of old

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X-ray emission properties vary with spin-down age

Crab-like pulsars
(< $10^4$ yrs)

Cooling neutron stars
(~$10^5$ - $10^6$ yrs)

Old pulsars
(~$10^6$ - $10^8$ yrs)
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- Cooling neutron stars
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Based on ROSAT + ASCA observations of PSR 1929+10

Diagrams showing log flux versus log energy for radio and X-ray emissions, with thermal and non-thermal components.
X-ray emission properties vary with spin-down age

Crab-like pulsars
(< 10⁴ yrs)

Cooling neutron stars
( ~10⁵ - 10⁶ yrs)

Old pulsars
(~10⁶ - 10⁸ yrs)

Based on ROSAT + ASCA obs. of PSR 1929+10

NEEDS REVISION
XMM-Newton observations of old pulsars

τ \sim 17 \times 10^6 \text{ yrs} \quad \sim 5 \times 10^6 \text{ yrs} \quad \sim 1.2 \times 10^6 \text{ yrs}

P \sim 253 \text{ ms} \quad \sim 530 \text{ ms} \quad \sim 96 \text{ ms}

\dot{E} \sim 5.6 \times 10^{32} \text{ erg/s} \quad \sim 4.5 \times 10^{32} \text{ erg/s} \quad \sim 5.6 \times 10^{34} \text{ erg/s}

d \sim 255 \text{ pc} \quad \sim 340 \text{ pc} \quad \sim 1130 \text{ pc}

N_H \sim 9.6 \times 10^{19} \text{ cm}^{-2} \quad \sim 60 \times 10^{19} \text{ cm}^{-2} \quad \sim 65 \times 10^{19} \text{ cm}^{-2}

Becker, Weisskopf, Tennant et al. (2004)
X-ray emission properties of old pulsars

- A single BB spectrum can safely be excluded
- The simplest model which fits best is a PL → non-thermal emission dominates
- PL fit so good that in composite models the BB intrinsically appears to be an upper limit
- in J2043+1740 some thermal contr. possible

$\alpha = 1.93^{+0.14}_{-0.12}$
$\alpha = 2.5^{+0.9}_{-0.45}$
$\alpha = 3.1^{+1.1}_{-0.6}$

Becker, Weisskopf, Tennant et al. (2004)
X-ray emission properties of old pulsars: B0950+08

- Pulse profile NOT sinusoidal
- Double peaked pulse profile
- Phase separation between X-ray peaks $\sim 144^0$
  the same as for radio pulse and interpulse

$PF = 28 \pm 6\%$, phase separation $\sim 144^0$

Becker, Weisskopf, Tennant et al. (2004)
Multi-wavelength emission spectrum: B0950+08

Optical to X-ray data:

\[ \alpha_1 = 1.27^{+0.02}_{-0.01} \]
\[ \alpha_2 = 1.88^{+0.14}_{-0.11} \]
\[ E_{\text{break}} = 0.67^{+0.18}_{-0.41} \]

Optical data taken with the VLT FORS1 (Zharikov et al. 2003)
Radio data from Malofeev et al. (1994)

Becker, Weisskopf, Tennant et al. (2004)
XMM-Newton observations of old pulsars: B0628-28

\[ \tau \sim 2.75 \times 10^6 \text{ yrs} \]
\[ P \sim 1.24 \text{ s} \]
\[ \dot{E} \sim 1.45 \times 10^{32} \text{ erg/s} \]
\[ d \sim 1.45 \text{ kpc} \]
\[ N_H \sim 6 \times 10^{20} \text{ cm}^{-2} \]

PF = 39 ± 6% (0.2 - 10 keV)

Becker, Jessner, Kramer et al. (2005)
XMM-Newton observations of old pulsars: B0628-28

- single PL spectrum fits best
  → non-thermal emission dominates
- some thermal contrib. possible

Becker, Jessner, Kramer et al. (2005)
X-ray emission properties of old pulsars: B1929-10

$\tau \sim 3.1 \times 10^6$ yrs
$P \sim 226$ ms
$\dot{E} \sim 3.9 \times 10^{33}$ erg/s
$d \sim 3.178$ pc
$N_H \sim 6 \times 10^{20}$ cm$^{-2}$

$PF = 32 \pm 4\% \ (0.2 - 10$ keV$)$

X-ray emission properties of old pulsars: B1929-10


PF = 24 ± 5%

PF = 44 ± 6%
X-ray emission properties of old pulsars: B1929-10

- Single BB spectrum excluded
- single PL spectrum fits best
  → non-thermal emission dominates
- best fitting PL allows for a
  7% thermal contribution from PC

**B1929+10**

\[ \alpha = 2.72^{+0.12}_{-0.09} \]

ROSAT + XMM-Newton (MOS1/2 & PN)

X-ray emission properties of old pulsars: B1929-10

X-ray emission properties of old pulsars: B1929-10

- length of the trail not very well constraint \(\rightarrow\) requires deeper observations !!

X-ray emission properties of old pulsars: B1929-10

X-ray emission properties of old pulsars: B1929-10

- spectrum non-thermal
- likely from synchrotron processes in the shocked region between pulsar wind and the ISM

X-ray emission properties of old pulsars: B1929-10

Effelsberg 11cm galactic plane survey

NRAO VLA Sky survey (1.4 GHz)

Summary of rot. powered pulsars detected at X

- With EINSTEIN & EXOSAT: 7 radio pulsars detected in X-rays
- With ROSAT, ASCA & BSAX: 33 radio pulsars detected in X-rays
- After ~7 yrs with XMM & Chandra: 78 radio pulsars detected in X-rays

<table>
<thead>
<tr>
<th>Age $\tau$</th>
<th>Pulsar category</th>
<th>ROSAT/ASCA</th>
<th>XMM/Chandra</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt; 10^4$ yrs</td>
<td>Crab-like</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>$10^4 - 10^5$ yrs</td>
<td>Vela-like</td>
<td>9</td>
<td>15</td>
</tr>
<tr>
<td>$10^5 - 10^6$ yrs</td>
<td>Cooling NS</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$10^6 - 10^8$ yrs</td>
<td>Old &amp; nearby</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>other</td>
<td>1</td>
<td>2</td>
<td>+1</td>
</tr>
<tr>
<td>$&gt; 10^8$ yrs</td>
<td>ms-Pulsars</td>
<td>11</td>
<td>39</td>
</tr>
</tbody>
</table>

detected # 33 78 +45
- non-thermal emission dominates in old pulsars / pulse profiles \textbf{NOT} sinusoidal

- hot polar cap emission component may decrease along with the cooling surface component?

- if so, hot polar caps in cooling neutron stars are probably formed by anisotropic heat flow due to the presence of the magnetic field rather than by particle bombardment
X-ray emission properties of old pulsars

No evidence for a spectral softening with increasing spin-down age