PULSARS

X-ray emission properties of old

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Progress in Pulsar detection

- With EINSTEIN & EXOSAT:
  7 radio pulsars detected in X-rays
- With ROSAT, ASCA & BSAX:
  33 radio pulsars detected in X-rays
- After ~8 yrs with XMM & Chandra:
  81 radio pulsars detected in X-rays
- 8 pulsars fall into the category of old and nearby neutron stars

Becker, Haberl & Trümper 2007
X-ray emission properties vary with spin-down age

Crab-like pulsars

(< $10^4$ yrs)

Fraction of pulsed photons $\sim 100\%$
X-ray emission properties vary with spin-down age

Crab-like pulsars
(< 10^4 yrs)

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

Fraction of pulsed photons ~100%
Fraction of pulsed photons ~20-30%
X-ray emission properties vary with spin-down age

- **Crab-like pulsars**
  - (< $10^4$ yrs)
  - Fraction of pulsed photons ~100%

- **Cooling neutron stars**
  - (~$10^5$ - $10^6$ yrs)
  - Fraction of pulsed photons ~20-30%

- **Old pulsars**
  - (~$10^6$ - $10^8$ yrs)
Crab-like pulsars
(< $10^4$ yrs)

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

Old pulsars
( ~$10^6$ - $10^8$ yrs)

Based on ROSAT obs. of PSR 1929+10 only

Fraction of pulsed photons ~100%

Fraction of pulsed photons ~20-30%

Sinusoidal
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 obs. of PSR 1929+10 only

Fraction of pulsed photons 
- Crab-like: ~100%
- Cooling neutron stars: ~20-30%
- Old pulsars: sinusoidal

**NEEDS REVISION**
XMM-Newton observations of old pulsars

Becker, Weisskopf, Tennant et al. (2004)

\[ \tau \sim 17 \times 10^6 \text{ yrs} \]
\[ d \sim 255 \text{ pc} \]
\[ N_H \sim 9.6 \times 10^{19} \text{ cm}^{-2} \]
\[ \dot{E} \sim 5.6 \times 10^{32} \text{ erg/s} \]

\[ \sim 5 \times 10^6 \text{ yrs} \]
\[ \sim 340 \text{ pc} \]
\[ \sim 60 \times 10^{19} \text{ cm}^{-2} \]
\[ \sim 4.5 \times 10^{32} \text{ erg/s} \]

\[ \sim 1.2 \times 10^6 \text{ yrs} \]
\[ \sim 1130 \text{ pc} \]
\[ \sim 65 \times 10^{19} \text{ cm}^{-2} \]
\[ \sim 5.6 \times 10^{34} \text{ erg/s} \]
X-ray emission properties of old pulsars

- BB spectra are clearly excluded
- BB+BB model resulted in an emitting area for possible polar caps of \( \sim \) cm size
- **Simplest model**: single PL spectrum fits best

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

- Pulse profile is **NOT sinusoidal**
- Double peaked pulse profile
- Phase separation between X-ray peaks of ~ 144°, the same as for radio pulse and interpulse

\[ PF = 28 \pm 6\%, \quad \text{phase separation} \sim 144^\circ \]

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

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

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

- BB spectra are clearly excluded
- single PL spectrum fits best
  → non-thermal emission dominates
- ~ 20% thermal contrib. possible

\[ \alpha = 2.63^{+0.22}_{-0.15} \]

Becker, Jessner, Kramer et al. (2005)
The prototype of an old pulsar: PSR B1929-10

\[ \tau \sim 3.1 \times 10^6 \text{ yrs} \]
\[ P \sim 226 \text{ ms} \]
\[ \dot{E} \sim 3.9 \times 10^{33} \text{ erg/s} \]
\[ d \sim 317.8 \text{ pc} \]

Becker, Kramer, Jessner et al. (2006)
The prototype of an old pulsar: PSR B1929-10

PF = 32 ± 4% (0.2 - 10 keV)

Becker, Kramer, Jessner et al. (2006)
The prototype of an old pulsar: PSR B1929-10

PF = 44 ± 6%  \(>1\) keV

PF = 24 ± 5%  \(<1\) keV

Becker, Kramer, Jessner et al. (2006)
The prototype of an old pulsar: PSR B1929-10

\[ \alpha = 2.72^{+0.12}_{-0.09} \quad N_H / 10^{21} = 1.6^{+0.2}_{-0.18} \]

- single PL spectrum fits best → non-thermal emission dominates
The prototype of an old pulsar: PSR B1929-10

Becker, Kramer, Jessner et al. (2006)

**Fig. 12.** Blackbody plus power law spectral components and combined model as fitted to the spectral data of PSR B1929-10.

BB+PL fit: in stretching the errors to the limits no more than ~40% of the emission could come from heated polar caps.
Pulsar Bow-Shocks......
Proper motion with $V$

If the ram pressure $p_{\text{ram}} = \rho_{\text{amb}} V^2$ exceeds the ambient gas pressure a bow-shock is formed.
The pulsar is moving at a transverse velocity of 177 km/s.

The trail emission is non-thermal and is likely produced from the synchrotron process of highly relativistic electrons in the shocked region between the pulsar wind and the surrounding ISM.

Becker, Kramer, Jessner et al. (2006)
X-ray emission properties of old pulsars: B1929-10

Becker, Kramer, Jessner et al. (2006)
X-ray emission properties of old pulsars: B1929-10

- length of the trail not very well constraint → requires deeper observations !!

Becker, Kramer, Jessner et al. (2006)
**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

\[
\alpha = 2.0^{+0.4}_{-0.4}
\]

\[
N_H / 10^{21} = 0.6^{+0.7}_{-0.6}
\]
Resolving the bow-shock nebula around the old pulsar PSR B1929+10

Resolving the bow-shock nebula around the old pulsar PSR B1929+10

X-ray emission prop. scale with spin-down age

- non-thermal emission dominates in old pulsars / pulse profiles are NOT sinusoidal
- Diffuse bow-shock emission of these low $E_{dot}$ pulsars has the potential to challenge pulsar-wind models
X-ray emission properties of old pulsars

No evidence for a spectral softening with increasing spin-down age for old pulsars.
Surface temperature upper limits for $R_{NS}=10$ km

<table>
<thead>
<tr>
<th>Pulsar</th>
<th>Spin down age</th>
<th>$T_s^\infty$ 3σ upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2224+65</td>
<td>1.13 x 10^6 yrs</td>
<td>&lt; 0.68 10^6 k</td>
</tr>
<tr>
<td>J2043+2740</td>
<td>1.2 x 10^6 yrs</td>
<td>&lt; 0.62 10^6 k</td>
</tr>
<tr>
<td>B0628-28</td>
<td>2.75 x 10^6 yrs</td>
<td>&lt; 0.53 10^6 k</td>
</tr>
<tr>
<td>B1929+10</td>
<td>3.1 x 10^6 yrs</td>
<td>&lt; 0.45 10^6 k</td>
</tr>
<tr>
<td>B0823+26</td>
<td>5 x 10^6 yrs</td>
<td>&lt; 0.5 10^6 k</td>
</tr>
<tr>
<td>B0950-09</td>
<td>17 x 10^6 yrs</td>
<td>&lt; 0.48 10^6 k</td>
</tr>
</tbody>
</table>
X-ray emission properties of old pulsars

\[ \log L_x (0.1-2.4 \text{ keV}) \text{ (ergs/s)} \]

- Best fit with \( L_x = 10^{(3.1 \pm 0.2)} \frac{dE}{dt} \)

- B0628-28
- B0823+26
- B0943+10
- B1133+16
- B1929+10
- J2042+2740

\[ \log \frac{dE}{dt} \text{ (ergs/s)} \]
Neutron star temperature measurements

Becker, Haberl & Trümper 2007