Nearby radio-quiet isolated neutron stars with strong magnetic fields

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Magnetic field estimates
• X-ray pulsations
  Spin period history
• X-ray spectrum
  Absorption features
  Variations with pulse phase
  Variations on long-term time scales
  Cyclotron lines – Harmonics?
  Atomic transition lines?

Neutron Stars at the Crossroads of Fundamental Physics
Vancouver, Canada, 9-13 August 2005
Thermal, radio-quiet isolated neutron stars

- Soft X-ray sources in ROSAT survey
- Blackbody-like X-ray spectra, NO non-thermal hard emission
- Low absorption $\sim 10^{20}$ H cm$^{-2}$, nearby, parallax for RX J1856.5-3754: 117 pc
- Luminosity $\sim 10^{31}$ erg s$^{-1}$ (dim)
- Constant X-ray flux on time scales of years (RX J0720.4–3125 ?)
- No obvious association with SNR
- No radio emission
- Optically faint
- Some (all?) are X-ray pulsars (3.45 – 11.37 s)

**best candidates for „genuine“ INSs with undisturbed emission from stellar surface**

<table>
<thead>
<tr>
<th>Object</th>
<th>kT/eV</th>
<th>P/s</th>
<th>Optical</th>
</tr>
</thead>
<tbody>
<tr>
<td>RX J0420.0–5022</td>
<td>44</td>
<td>3.45</td>
<td>B = 26.6</td>
</tr>
<tr>
<td>RX J0720.4–3125</td>
<td>85-95</td>
<td>8.39</td>
<td>B = 26.6</td>
</tr>
<tr>
<td>RX J0806.4–4123</td>
<td>96</td>
<td>11.37</td>
<td>B &gt; 24</td>
</tr>
<tr>
<td>RBS 1223 (*)</td>
<td>86</td>
<td>10.31</td>
<td>$m_{50\text{ccd}} = 28.6$</td>
</tr>
<tr>
<td>RX J1605.3+3249</td>
<td>96</td>
<td></td>
<td>B = 27.2</td>
</tr>
<tr>
<td>RX J1856.5–3754</td>
<td>60</td>
<td></td>
<td>V = 25.7</td>
</tr>
<tr>
<td>RBS 1774 (**)</td>
<td>101</td>
<td>9.44</td>
<td>R &gt; 23</td>
</tr>
</tbody>
</table>

(*) 1RXS J130848.6+212708  (**) 1RXS J214303.7+065419
### The Magnificent Seven

**Soft X-ray spectrum + faint in optical**

<table>
<thead>
<tr>
<th>PSPC cts/s</th>
<th>HR1</th>
<th>HR2</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15 ± 0.01</td>
<td>-0.96 ± 0.03</td>
<td>-0.45 ± 0.73</td>
<td>RX J0420.0-5022</td>
</tr>
<tr>
<td>0.23 ± 0.03</td>
<td>-0.06 ± 0.12</td>
<td>-0.60 ± 0.17</td>
<td>RBS1774 = 1RXS J214303.7+065419</td>
</tr>
<tr>
<td>0.29 ± 0.02</td>
<td>-0.20 ± 0.08</td>
<td>-0.51 ± 0.11</td>
<td>RBS1223 = 1RXS J130848.6+212708</td>
</tr>
<tr>
<td>0.38 ± 0.03</td>
<td>-0.74 ± 0.02</td>
<td>-0.66 ± 0.08</td>
<td>RX J0806.4-4123</td>
</tr>
<tr>
<td>0.78 ± 0.02</td>
<td>-0.67 ± 0.02</td>
<td>-0.68 ± 0.04</td>
<td>RBS1556 = RX J1605.3+3249</td>
</tr>
<tr>
<td>1.82 ± 0.02</td>
<td>-0.82 ± 0.01</td>
<td>-0.77 ± 0.03</td>
<td>RX J0720.4-3125</td>
</tr>
<tr>
<td>3.08 ± 0.02</td>
<td>-0.96 ± 0.01</td>
<td>-0.94 ± 0.02</td>
<td>RX J1856.5-3754</td>
</tr>
</tbody>
</table>
X-ray pulsations

EPIC–pn (0.12–1.2 keV) Rev 0534

<table>
<thead>
<tr>
<th>Phase</th>
<th>Normalized Flux</th>
<th>8.39 s</th>
<th>11 %</th>
</tr>
</thead>
</table>

EPIC–pn (0.12–1.2 keV) RX J0806.4–4123

<table>
<thead>
<tr>
<th>Phase</th>
<th>Normalized Flux</th>
<th>11.37 s</th>
<th>6 %</th>
</tr>
</thead>
</table>

EPIC–pn (0.12–1.2 keV) 1RXS J130848.6+212708

<table>
<thead>
<tr>
<th>Phase</th>
<th>Normalized Flux</th>
<th>10.31 s</th>
<th>18 %</th>
</tr>
</thead>
</table>

EPIC–pn (0.12–0.7 keV) RX J0420.0–5022

<table>
<thead>
<tr>
<th>Phase</th>
<th>Normalized Flux</th>
<th>3.45 s</th>
<th>13 %</th>
</tr>
</thead>
</table>
Period history: RX J0720.4–3125 and RBS 1223

- **Period history:**
  - **RX J0720.4–3125**
  - **RBS 1223**

- **6 year coverage**
  - **P = 10.32 s**
  - **P = 8.39 s**
  - **dP/dt = (6.98 ± 0.02) x 10^{-14} s s^{-1}**
  - **τ = P/2(dP/dt) = 1.9 x 10^6 y**
  - **B = 2.4 x 10^{13} G**

- **Spin evolution still unclear**
- **Conservative upper limit:**
  - **dP/dt < 9 x 10^{-13} s s^{-1}**
  - **B < 10^{14} G**


**Kaplan & van Kerkwijk 2005**

*ApJ 628, L45*
Soft, thermal X-ray spectra

\begin{align*}
    n_H & = (9.5 \pm 0.03) \times 10^{19} \text{ cm}^{-3} \\
    kT_\infty & = 63.5 \pm 0.2 \text{ eV} \\
    R_\infty & = 4.4 \pm 0.1 \text{ km (120pc)} \\
    L_{\text{bol}} & = 4.1 \times 10^{31} \text{ erg s}^{-1}
\end{align*}

\textit{Burwitz et al. (2003)}
X-ray spectral survey: black-body fits

RX J1856.5–3754  RX J0420.0–5022  RBS 1223

RX J0806.4–4123  RX J1605.3+3249  RX J0720.4–3125
X-ray spectral survey: absorption features

RBS 1223
kT = 95 eV
N_H = 7.1 x 10^{20} \text{ cm}^{-2}
E_{\text{line}} \sim 300 \text{ eV}
\sigma \sim 100 \text{ eV}
EW = 150 \text{ eV} 

RX J0720.4-3125
kT = 85 eV
N_H = 9 \times 10^{19} \text{ cm}^{-2}
E_{\text{line}} = 271 \pm 14 \text{ eV}
\sigma = 66 \pm 7 \text{ eV}
EW = 40 \text{ eV}

Haberl et al. (2003)  
Haberl et al. (2004)
X-ray spectral survey: absorption features

RBS 1223
EW = 150 eV

RX J0720.4-3125
EW = 40 eV

RX J1605.3+3249
RGS
kT = 95 eV
N_H = 0.8 \times 10^{20} \text{ cm}^{-2}
E_{\text{line}} = 450 – 480 eV

Van Kerkwijk et al. (2004)
Spectral variations with pulse phase

RX J0720.4-3125
Cropper et al. (2001)

RX J0420.0-5022

RX J0806.4-4123
Haberl et al. (2005)
RX J0720.4-3125: Variation of absorption line with pulse phase

Absorption line equivalent width varies between 30 eV to 60 eV. Small temperature variations by 2-3 eV.

*Haberl et al. (2004)*
Spectral variations with pulse phase

RBS 1223 (10.31s)  \textit{Schwope et al. 2005, A&A in press}

Two-spot model:  \( kT_\infty = 92 \text{ eV} \) and 84 eV

\( 2\Phi \sim 8^\circ \) and \( \sim 10^\circ \)

offset \( \sim 20^\circ \)
Long-term spectral changes from RX J0720.4-3125

Precession of the neutron star?

_de Vries et al. (2004)_
RX J0720.4-3125: Variation of absorption line with time

Absorption line equivalent width varies by a factor of 10 over 5 years. Temperature variations by 8.5 eV.
RX J0720.4-3125: History of spectral evolution

XMM-Newton RGS
Chandra LETGS
XMM-Newton EPIC-pn

provided by J. Vink
The case of 1E 1207.4-5209: X-ray spectrum

Absorption lines @ 0.68 keV, 1.36 keV, 2.14 keV? and 2.83 keV?  

Bignami et al. (2003)
$\chi^2 = 1.55$

$\chi^2 = 1.37$

$\chi^2 = 2.39$

$\chi^2 = 1.44$
RX J1605.3+3249: Multiple lines?

- Black-body: $\chi^2 = 4.38$
- +1 Gaussian: $\chi^2 = 2.39$
- +2 Gaussian: $\chi^2 = 1.75$
- +3 Gaussian: $\chi^2 = 1.39$
RX J1605.3+3249: Three absorption lines!

<table>
<thead>
<tr>
<th>Line energies:</th>
<th>Absorbed line fluxes:</th>
</tr>
</thead>
<tbody>
<tr>
<td>E₁ = 403 ± 2 eV</td>
<td>N₁ = -(4.3 ± 0.1) \cdot 10^{-3} \text{ ph/cm}²/s</td>
</tr>
<tr>
<td>E₂ = 589 ± 4 eV</td>
<td>N₂ = -(8.0 ± 0.8) \cdot 10^{-4} \text{ ph/cm}²/s</td>
</tr>
<tr>
<td>E₃ = 780 ± 24 eV</td>
<td>N₃ = -(1.6 ± 0.4) \cdot 10^{-5} \text{ ph/cm}²/s</td>
</tr>
<tr>
<td>E₂/E₁ = 1.46 ± 0.02</td>
<td>N₁/N₂ = 5.38 ± 0.54</td>
</tr>
<tr>
<td>E₃/E₁ = 1.94 ± 0.06</td>
<td>N₂/N₃ = 5.00 ± 1.35</td>
</tr>
<tr>
<td>E₃/E₂ = 1.32 ± 0.04</td>
<td></td>
</tr>
<tr>
<td>E₁ : E₂ : E₃ = 2 : 3 : 4</td>
<td></td>
</tr>
</tbody>
</table>

(EQW₁ = 96 eV, EQW₂ = 76 eV, EQW₃ = 67 eV)

Harmonic lines: fundamental line at 200 eV? Atomic line transitions?
Caused by protons or electrons? Hydrogen ruled out?
More harmonic lines?

**One line:**

\[ E_1 = 433 \pm 16 \text{ eV} \]

\[ \sigma_1 = 100 \text{ eV fixed} \]

**Two lines:**

\[ E_1 = 306 \pm 3 \text{ eV} \quad E_2 = 612 \text{ eV (linked to } E_1) \]

\[ \sigma_1 = \sigma_2 = 139 \pm 6 \text{ eV} \]

\[ N_1/N_2 = 16.6 \]
Summary, Magnetic fields

• Magnetic dipole braking → \( B = 3.2 \times 10^{19} \ (P \times dP/dt)^{1/2} \)
  Spin-down rate (P, dP/dt)
  Spin-down luminosity required to power the H\(\alpha\) nebula (dE/dt, \(\tau\))
• Proton cyclotron absorption → \( B = 1.6 \times 10^{11} \ E(eV)/(1-2GM/c^2R)^{1/2} \)

<table>
<thead>
<tr>
<th>Object</th>
<th>P [s]</th>
<th>Semi Ampl.</th>
<th>dP/dt [10^{-13} ss^{-1}]</th>
<th>(E_{cyc}) [eV]</th>
<th>B(_{db}) [10^{13} G]</th>
<th>B(_{cyc}) [10^{13} G]</th>
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<tbody>
<tr>
<td>RX J0420.0–5022</td>
<td>3.45</td>
<td>13%</td>
<td>&lt; 92</td>
<td></td>
<td>&lt; 18</td>
<td></td>
</tr>
<tr>
<td>RX J0720.4–3125</td>
<td>8.39</td>
<td>8-15%</td>
<td>0.698(2)</td>
<td>308</td>
<td>2.4</td>
<td>6.2</td>
</tr>
<tr>
<td>RX J0806.4–4123</td>
<td>11.37</td>
<td>6%</td>
<td>&lt; 18</td>
<td>430/306</td>
<td>&lt; 14</td>
<td>8.6/6.1</td>
</tr>
<tr>
<td>1RXS J130848.6+212708</td>
<td>10.31</td>
<td>18%</td>
<td>&lt; 9</td>
<td>302</td>
<td>&lt; 10</td>
<td>6.0</td>
</tr>
<tr>
<td>RX J1605.3+3249</td>
<td></td>
<td></td>
<td>200</td>
<td></td>
<td></td>
<td>3.2</td>
</tr>
<tr>
<td>RX J1856.5–3754</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>~1</td>
<td></td>
</tr>
<tr>
<td>1RXS J214303.7+212708</td>
<td>9.43</td>
<td>4%</td>
<td>~700</td>
<td></td>
<td>~14</td>
<td></td>
</tr>
</tbody>
</table>

Which lines are fundamental?
Is RX J1605.3+3249 still consistent with cyclotron absorption by protons?
Atomic line transitions?
Pure dipole fields (RBS 1223)?
Long spin periods + age of 10^6 years (cooling and dP/dt) require high B