The Magnificent Seven - Nearby Cooling Neutron Stars with $10^{13}$ Gauss Magnetic Fields

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The ROSAT discovery of thermal, radio quiet isolated neutron stars
New XMM-Newton and Chandra observations
- Magnetic field estimates
  - Absorption features in the X-ray spectra
  - Pulse timing
- The case of RX J0720.4-3125
  - Spectral variations on long-term time scales
  - Evidence for free precession

Fenomec Mini Workshop on Magnetic Fields and Neutron Stars Surface
Cocoyoc, Mexico, February 12 - 14, 2007
The Magnificent Seven: Thermal, radio-quiet neutron stars

Soft X-ray spectrum + faint in optical

Haberl et al. (1997)

Walter et al. (1996)

<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>
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<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>
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<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>
The X-ray spectrum of RX J1856.5–3754

\[ n_H = (9.5 \pm 0.03) \cdot 10^{19} \text{ cm} \]
\[ kT_\infty = 63.5 \pm 0.2 \text{ eV} \]
\[ R_\infty = 4.4 \pm 0.1 \text{ km (120pc)} \]
\[ L_{\text{bol}} = 4.1 \cdot 10^{31} \text{ erg s}^{-1} \]

No narrow absorption features!

*Burwitz et al. (2003)*

Spectrum constant over time scales of years

*Haberl (2006)*
Thermal, radio-quiet isolated neutron stars

- Soft X-ray sources in ROSAT survey + optically faint → isolated neutron stars
- Blackbody-like X-ray spectra, NO non-thermal hard emission
- Low absorption $\sim 10^{20}$ H cm$^{-2}$ → nearby (2 cases with measured parallax)
- Luminosity $\sim 10^{31}$ erg s$^{-1}$
- Constant X-ray flux on time scales of years
- No obvious association with SNR
- No (faint?) radio emission (RBS1223, RBS1774)
- Probably all are X-ray pulsars (3.45 – 11.37 s)

Best candidates for „genuine“ cooling INSs with undisturbed emission from stellar surface

<table>
<thead>
<tr>
<th>Object</th>
<th>T/$10^6$ K</th>
<th>kT/eV</th>
<th>P/s</th>
<th>Optical</th>
<th>PM/mas/y</th>
<th>distance/pc</th>
</tr>
</thead>
<tbody>
<tr>
<td>RX J0420.0–5022</td>
<td>0.51</td>
<td>44</td>
<td>3.45</td>
<td>B = 26.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RX J0720.4–3125</td>
<td>0.99-1.10</td>
<td>85-95</td>
<td>8.39</td>
<td>B = 26.6</td>
<td>97</td>
<td>330 +170/-80</td>
</tr>
<tr>
<td>RX J0806.4–4123</td>
<td>1.11</td>
<td>96</td>
<td>11.37</td>
<td>B &gt; 24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RX J1308.8+2127*</td>
<td>1.00</td>
<td>86</td>
<td>10.31</td>
<td>m$_{50c}$ = 28.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RX J1605.3+3249</td>
<td>1.11</td>
<td>96</td>
<td>6.88?</td>
<td>B = 27.2</td>
<td>145</td>
<td></td>
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<tr>
<td>RX J1856.5–3754</td>
<td>0.73</td>
<td>62</td>
<td>7.06</td>
<td>B = 25.2</td>
<td>332</td>
<td>161 +18/-14</td>
</tr>
<tr>
<td>RX J2143.0+0654**</td>
<td>1.17</td>
<td>102</td>
<td>9.44</td>
<td>B &gt; 26</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* 1RXS J130848.6+212708 = RBS1223   ** 1RXS J214303.7+065419 = RBS 1774
RX J1856.5-3754: optical

Distance 161 +18/−14 pc

High proper motion:
Not heated by accretion of ISM !!
Cooling isolated neutron star

van Kerkwijk & Kaplan (2006)

HST

Powered by magnetic dipole braking:
\[ \frac{dE}{dt} = 4.5 \times 10^{32} \text{ erg s}^{-1}, \ t = 5 \times 10^5 \text{ y} \]
\[ B \approx 10^{13} \text{ G} \]

Braje & Romani (2002)
Trümper et al. (2004)
XMM-Newton observations of the M7: absorption features

RBS 1223
EW = 150 eV
Pulse phase variations

RX J0720.4-3125
EW = 40 eV variable with pulse phase and over years

RX J1605.3+3249
kT = 95 eV
N_H = 0.8 \cdot 10^{20} \text{ cm}^{-2}
E_{\text{line}} = 450 – 480 eV
Van Kerkwijk et al. (2004)
Evidence for multiple lines:

- blackbody: $\chi^2 = 1.55$
- blackbody+line: $\chi^2 = 1.44$
- blackbody+line: $\chi^2 = 1.37$
- blackbody+line: $\chi^2 = 2.39$
RX J1605.3+3249: Evidence for three 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 with regular energy spacing

Line energies:

\[ E_1 = 403 \pm 2 \text{ eV} \]
\[ E_2 = 589 \pm 4 \text{ eV} \]
\[ E_3 = 780 \pm 24 \text{ eV} \]
\[ E_2/E_1 = 1.46 \pm 0.02 \]
\[ E_3/E_1 = 1.94 \pm 0.06 \]
\[ E_3/E_2 = 1.32 \pm 0.04 \]
\[ E_1 : E_2 : E_3 = 1 : 1.5 : 2 \]

Absorbed line fluxes:

\[ N_1 = -\left(4.3 \pm 0.1\right) \times 10^{-3} \text{ ph/cm}^2/\text{s} \]
\[ N_2 = -\left(8.0 \pm 0.8\right) \times 10^{-4} \text{ ph/cm}^2/\text{s} \]
\[ N_3 = -\left(1.6 \pm 0.4\right) \times 10^{-5} \text{ ph/cm}^2/\text{s} \]
\[ N_1/N_2 = 5.38 \pm 0.54 \]
\[ N_2/N_3 = 5.00 \pm 1.35 \]
\[ N_1 : N_2 : N_3 \sim 25 : 5 : 1 \]

(common line \( \sigma = 87 \text{ eV} \))

EQW1 = 96 eV
EQW2 = 76 eV
EQW3 = 67 eV

RBS1223: Evidence for lines at 230 eV and at 460 eV (Schwope et al. 2006, London)
RX J0806.4-4123: also two lines?
The origin of the absorption features

Proton cyclotron absorption line?
In the case of proton scattering harmonics should be greatly suppressed.

Atomic line transitions?
Hydrogen?
Mixture?

van Kerkwijk & Kaplan 2006, astro-ph/0607320

In any case $B \approx 10^{13} - 10^{14} \, \text{G}$
X-ray pulsations

- **EPIC–pn (0.12–1.2 keV) Rev 0534 (RX J0720.4–3125)**
  - 8.39 s
  - 11% variable

- **EPIC–pn (0.12–1.2 keV) (RX J0806.4–4123)**
  - 11.37 s
  - 6%

- **EPIC–pn (0.12–1.2 keV) (IRXS J130848.6+21270B)**
  - 10.31 s
  - 18%

- **EPIC–pn (0.12–0.7 keV) (RXJ0420.0–5022)**
  - 3.45 s
  - 13%
Period history: RX J0720.4–3125 and RBS 1223

\[ P = 8.39 \text{ s} \]
\[ \frac{dP}{dt} = (0.698 \pm 0.002) \cdot 10^{-13} \text{ s s}^{-1} \]
\[ \tau = \frac{P}{2(dP/dt)} = 1.9 \cdot 10^6 \text{ y} \]
\[ B = 2.4 \cdot 10^{13} \text{ G} \]

Kaplan & van Kerkwijk 2005
ApJ 628, L45

\[ P = 10.32 \text{ s} \]
\[ \frac{dP}{dt} = (1.120 \pm 0.003) \cdot 10^{-13} \text{ s s}^{-1} \]
\[ \tau = \frac{P}{2(dP/dt)} = 1.5 \cdot 10^6 \text{ y} \]
\[ B = 3.4 \cdot 10^{13} \text{ G} \]

Kaplan & van Kerkwijk 2005
ApJ 635, L65
Magnetic fields

Unique opportunity to estimate B in two independent ways:
• Magnetic dipole braking \( \rightarrow B = 3.2 \times 10^{19} (P \times \frac{dP}{dt})^{1/2} \)
  Spin-down rate (P, \( \frac{dP}{dt} \))
  Spin-down luminosity required to power the H\(\alpha\) nebula (dE/dt, \(\tau\))
• Proton cyclotron absorption \( \rightarrow B = 1.6 \times 10^{11} \frac{E(\text{eV})}{(1-2GM/c^2R)^{1/2}} \)

<table>
<thead>
<tr>
<th>Object</th>
<th>P [s]</th>
<th>Semi Ampl.</th>
<th>( \frac{dP}{dt} ) [10^{-13} \text{ ss}^{-1}]</th>
<th>E(_{\text{abs}}) [eV]</th>
<th>B(_{\text{db}}) [10^{13} \text{ G}]</th>
<th>B(_{\text{cyc}}) [10^{13} \text{ G}]</th>
</tr>
</thead>
<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>280</td>
<td>2.4</td>
<td>5.6</td>
</tr>
<tr>
<td>RX J0806.4–4123</td>
<td>11.37</td>
<td>6%</td>
<td>&lt;18</td>
<td>430/306(^a)</td>
<td>&lt;14</td>
<td>8.6/6.1</td>
</tr>
<tr>
<td>1RXS J1308.8+2127</td>
<td>10.31</td>
<td>18%</td>
<td>1.120(3)</td>
<td>300/230(^a)</td>
<td>3.4</td>
<td>6.0/4.6</td>
</tr>
<tr>
<td>RX J1605.3+3249</td>
<td>6.88?</td>
<td></td>
<td></td>
<td>450/400(^b)</td>
<td>9/8</td>
<td></td>
</tr>
<tr>
<td>RX J1856.5–3754</td>
<td>7.06</td>
<td>1.5%</td>
<td>&lt;19</td>
<td>–</td>
<td>4.2(^c)</td>
<td>–</td>
</tr>
<tr>
<td>1RXS J2143.0+0654</td>
<td>9.43</td>
<td>4%</td>
<td>&lt;60(^d)</td>
<td>750</td>
<td>&lt;24(^d)</td>
<td>15</td>
</tr>
</tbody>
</table>

\(^a\) Spectral fit with single line / two lines
\(^b\) With single line / three lines at 400 eV, 600 eV and 800 eV
\(^c\) Based on age of 5x10\(^5\) years
  Estimate from H\(\alpha\) nebula assuming that it is powered by magnetic dipole breaking: \(\sim 1 \times 10^{13} \text{ G}\)
\(^d\) Radio detection: Malofeev et al. 2006, ATEL 798
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)
Spectral variations with pulse phase: RBS 1223

RBS 1223 (10.31s)  
Schwope et al. 2005

Two-spot model:  \( kT_\infty = 92 \text{ eV and } 84 \text{ eV} \)
\[ 2\Phi \sim 8^\circ \text{ and } 10^\circ \]
offset \( \sim 20^\circ \)
Long-term spectral changes from RX J0720.4-3125

Increase at short wavelength: temperature increase
Decrease at long wavelength: deeper absorption line

Increase in pulsed fraction

Precession of the neutron star?

*de Vries et al. (2004)*
RX J0720.4-3125 longterm spectral variations

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RX J0720.4-3125: Spectral variations over 4.5 years

Long-term variations over 5.5 years:
- Temperature by ~7 eV
- Absorption line equivalent width by ~70 eV
- Radius of emission area from 4.4 km to 4.8 km (d=300pc)
- But flux is constant within ±2%

<table>
<thead>
<tr>
<th>Rev.</th>
<th>kT(eV)</th>
<th>EW(eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0078</td>
<td>86.6 ± 0.4</td>
<td>–5.02 ± 4.5</td>
</tr>
<tr>
<td>0175</td>
<td>86.5 ± 0.5</td>
<td>+8.68 ± 7.7</td>
</tr>
<tr>
<td>0533/534</td>
<td>88.3 ± 0.3</td>
<td>–21.5 ± 2.6</td>
</tr>
<tr>
<td>0711/711</td>
<td>91.3 ± 0.6</td>
<td>–73.7 ± 4.9</td>
</tr>
<tr>
<td>0815</td>
<td>93.8 ± 0.4</td>
<td>–72.4 ± 4.7</td>
</tr>
<tr>
<td>0986</td>
<td>93.5 ± 0.4</td>
<td>–68.3 ± 5.2</td>
</tr>
<tr>
<td>1060</td>
<td>93.2 ± 0.4</td>
<td>–67.4 ± 4.3</td>
</tr>
<tr>
<td>1086</td>
<td>92.6 ± 0.4</td>
<td>–67.5 ± 3.5</td>
</tr>
</tbody>
</table>

• FF mode + thin filter

common line energy: 280 ± 6 eV
common line width: σ = 90 ± 5 eV
RX J0720.4-3125 longterm spectral variations

Sinusoidal variations in spectral parameters
Period 7.1 ± 0.5 years

Sinusoidal variations in pulse timing
Period 7.7 ± 0.6 years

Free precession of an isolated neutron star with period 7–8 years
\[ \varepsilon = \frac{(I_3 - I_1)}{I_1} = \frac{P_{\text{spin}}}{P_{\text{prec}}} \approx 4 \times 10^{-8} \]  (moments of inertia for a rigid body)
between that reported from of radio pulsars and Her X-1
RX J0720.4-3125 pulse phase spectral variations
RX J0720.4-3125: Spectral variations over pulse and precession phase

13–05–2000 (rev 0078)
06–11–2002 (rev 0533/534)
22–05–2004 (rev 0815)
28–04–2005 (rev 0986)
23–09–2005 (rev 1060)
12–11–2005 (rev 1086)
RX J0720.4-3125: A precessing isolated neutron star

The model:
Two hot polar caps
  with different temperature
  with different size
  the hotter is smaller: T–R anti-correlation
  
  \[ T_1 = 80 \text{ eV} \sin \theta_1 = 0.8 \]
  
  \[ T_2 = 100 \text{ eV} \sin \theta_2 = 0.6 \]

  not exactly antipodal:
  phase shift of lag between hard
  and soft emission
  \[ \theta_0 = 160^\circ \]

See also: Perez-Azorin et al. (2006)
RX J0720.4-3125: A precessing isolated neutron star

Roberto Turolla
Cor P. De Vries
Silvia Zane
Jacco Fink
Mariano Mendez
Frank Verbunt

Haberl et al. 2006
A&A 451, L17

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Pulsars

magnetic dipole braking: age = P / 2\dot{P}, B = 3.2 \times 10^{19} (P\dot{P})^{1/2}

high-energy detections (incomplete)

AXPs / SGRs (magnetars)

Magnificent Seven:
circles: P/\dot{P}
diamonds: cyclotron lines
The inhomogenous Interstellar Medium (B. Posselt)

Henbest & Couper 1994

Lallement et al. 2003 (NaD)
Breitschwerdt et al. 2005

~1700 pc

The inhomogenous Interstellar Medium (B. Posselt)

Henbest & Couper 1994

Lallement et al. 2003 (NaD)
Breitschwerdt et al. 2005

~1700 pc

~1300 pc

Within one kpc around the sun

The close solar neighbourhood

The inhomogenous Interstellar Medium (B. Posselt)

Henbest & Couper 1994

Lallement et al. 2003 (NaD)
Breitschwerdt et al. 2005

~1700 pc

~1300 pc

Within one kpc around the sun

The close solar neighbourhood
In the direction of RX J1856.5-3754 (l = 359°, b = -17°)

Kaplan et al. 2002 : 140 ± 40 pc
Kerkwijk & Kaplan 2006 : 147–179 pc

towards R CrA
@ 130 pc : 0.7 x 10^{20} cm^{-2}
@ 140 pc : 1.0 x 10^{20} cm^{-2}

<table>
<thead>
<tr>
<th>Source</th>
<th>N(H) [10^{20} cm^{-2}]</th>
<th>Distance [pc]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RX J1856.5-3754</td>
<td>0.7 (0L)</td>
<td>120-140</td>
</tr>
<tr>
<td>RX J0420.0-5022</td>
<td>1.6 (1L)</td>
<td>320-350</td>
</tr>
<tr>
<td>RX J0720.4-3125</td>
<td>1.2 (1L)</td>
<td>230-280</td>
</tr>
<tr>
<td>RX J0806.4-4123</td>
<td>1.0 (1L)</td>
<td>230-260</td>
</tr>
<tr>
<td>RBS 1223</td>
<td>4.3 (1L)</td>
<td>-</td>
</tr>
<tr>
<td>RX J1605.3+3249</td>
<td>2.0 (3L)</td>
<td>320-400</td>
</tr>
<tr>
<td>RBS 1774</td>
<td>2.4 (1L)</td>
<td>380-440</td>
</tr>
</tbody>
</table>

Nearby INS and local stellar structures

Blue lines are possible INS positions assuming $d = 100 - 400$ pc

OB member locations after de Zeeuw et al. 1999

All XDINSs are located in a half sky centred on Sco OB2

Projected view on galactic plane
Where are the nearby Neutron Stars with $10^{12}$ Gauss?

- Heating by field decay?
- Lower overall cooling rate?
- Hotter polar caps?
The Magnificent Seven: Summary

\( \frac{F_x}{F_{opt}} > 10^4 \) → Isolated neutron stars
High proper motion → Nearby, cooling isolated neutron stars
d\( P/dt \) + absorption features → Magnetic fields \( 10^{13-14} \) G
Evidence for multiple lines → Proton cyclotron absorption + Atomic line transitions?

Interesting individuals:
RX J0720.4-3125: Pulsar, absorption feature → B field, kT distribution
Precession → A probe to the NS interior
RX J1856.4-3754: Weak pulsations, no absorption feature

State of the atmosphere (condensed)?
Composition of the atmosphere?
Origin of absorption features?
Individual differences (viewing effects) ?

Theoretical work on NS atmospheres (strong B fields)
Improved X-ray detectors (resolution + sensitivity)
X-ray monitoring
More optical observations (large telescopes)