The Magnificent Seven: 
Nearby, Thermally Emitting, Isolated Neutron Stars

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A legacy of ROSAT
Proper motions and distances
Observations with XMM-Newton and Chandra
  - Magnetic fields
    Pulse timing
    Absorption features in the X-ray spectra
  - Surface temperature distributions
Ages, cooling of neutron stars

The case of RX J0720.4-3125
  - Spectral and temporal variations on long-term time scales

The Fast and the Furious:
Energetic Phenomena in Isolated Neutron Stars, Pulsar Wind Nebulae and Supernova Remnants
ESAC, Madrid, Spain, 22-24 May 2013
A Legacy of ROSAT: The discovery of seven radio-quiet neutron stars

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

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

Blackbody-like X-ray spectra without non-thermal component!
Best candidates for „genuine“ cooling INSs with nearly undisturbed emission from stellar surface

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*Haberl et al. (1997)*

*Walter et al. (1996)*
The X-ray spectrum of RX J1856.5–3754

\[
\begin{align*}
n_H &= (9.5 \pm 0.03) \cdot 10^{19} \text{ cm} \\
kT_\infty &= 63.5 \pm 0.2 \text{ eV} \\
R_\infty &= 5.5 \pm 0.15 \text{ km (123pc)} \\
L_{bol} &= 4.3 \cdot 10^{31} \text{ erg s}^{-1}
\end{align*}
\]

No narrow absorption features!

Burwitz et al. (2003, 2004)

Spectrum constant over time scales of years

Haberl (2006)
Proper motions, distances and velocities

RX J1856.5-3754

B = 25.2
Proper motion = 330 mas y\(^{-1}\)
Parallax 8.16 +0.9/-0.8 mas (1\(\sigma\))
Distance = 123 +11/-15 pc
Tangential space velocity = 254 km s\(^{-1}\)
Kinematic age from back tracing to possible birth place \(\approx 5 \times 10^5\) y

\(\text{Walter et al. 2010}\)

see also Walter 2001, Kaplan et al. (2002), Walter & Lattimer 2002,
van Kerkwijk & Kaplan (2007)

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

\(\text{Bow shock Nebula}\)

\(\text{VLT}\)

\(\text{Kerkwijk & Kulkarni (2001)}\)

\(\text{Powered by magnetic dipole braking:}\)

\(\text{Braje & Romani (2002)}\)

\(\text{Trümper et al. (2004)}\)
The inhomogenous Interstellar Medium (B. Posselt)

Henbest & Couper 1994

Lallement et al. 2003 (NaI D-line)
Breitschwerdt et al. 2005

~1700 pc

~1300 pc

Galactic center

Within one kpc around the sun

The close solar neighbourhood

Diffuse HI Regions
Molecular Clouds
Nebulae
Star Associations

Taurus dark clouds
Pleiades bubble
Loop I
Tunnel to GSH 238+00
S Coalsack
Lupus Tunnel
Chamelecon

Ophiuchus clouds

Galactic center

z=0 pc

250 pc
-250 pc
250 pc

~1700 pc

~1300 pc

~1300 pc
In the direction of RX J1856.5-3754 
(\(l = 359^\circ, b = -17^\circ\))

Walter et al. 2010: 123 +11/−15 pc

towards R CrA

@ 130 pc: 0.7 \( \times \) 10\(^{20}\) cm\(^{-2}\)
@ 140 pc: 1.0 \( \times \) 10\(^{20}\) cm\(^{-2}\)

### Distance estimates from X-ray absorption

<table>
<thead>
<tr>
<th>Object</th>
<th>(N(H)) ([10^{20} \text{cm}^{-2}])</th>
<th>Distance ([\text{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>&gt;400</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>

### Proper motions, distances and velocities

<table>
<thead>
<tr>
<th>Object</th>
<th>μ (\text{mas y}^{-1})</th>
<th>distance (\text{pc})</th>
<th>(v_T) (\text{km s}^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>RX J0420.0–5022</td>
<td>&lt;123(^2)</td>
<td>(300–370)(^1)</td>
<td>&lt;200</td>
</tr>
<tr>
<td>RX J0720.4–3125</td>
<td>108±1</td>
<td>360 +172/-88</td>
<td>184</td>
</tr>
<tr>
<td></td>
<td></td>
<td>280 +210/-85</td>
<td>143(^4)</td>
</tr>
<tr>
<td>RX J0806.4–4123</td>
<td>&lt;86(^2)</td>
<td>(210–275)(^1)</td>
<td>&lt;96</td>
</tr>
<tr>
<td>RX J1308.8+2127</td>
<td>220±25(^2)</td>
<td>(400-800)(^1)</td>
<td>417-835</td>
</tr>
<tr>
<td>RX J1605.3+3249</td>
<td>155±3</td>
<td>(300–415)(^1)</td>
<td>286</td>
</tr>
<tr>
<td>RX J1856.5–3754</td>
<td>331±2</td>
<td>123 +11/-15(^3)</td>
<td>193</td>
</tr>
<tr>
<td>RX J2143.0+0654</td>
<td></td>
<td>(365–455)(^1)</td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) constraints from absorption  
\(^2\) X-ray measurements (Chandra)  
\(^3\) from Walter et al. 2010  
\(^4\) from Eissenbeiß 2011 (PhD thesis)

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High transverse speeds:  
No significant heating due to accretion from ISM !!
X-ray pulsations

Non-uniform temperature distribution on neutron star surface
X-ray pulsations

RX J2143.0+0654

RX J1856.5-3754

RX J1605.3+3249

\[ P = 3.388 \text{ s} \]

pulsed fraction \(~1.2\%\)

*Tiengo & Mereghetti 2007*

\[ P = 7.055 \text{ s} \]

pulsed fraction \(~1.2\%\)

Zane et al. 2005

\[ P = 9.437 \text{ s} \]

pulsed fraction \(~4\%\)

The M7 are pulsars with periods 3.39 – 11.37 s

\[ P = 3.388 \text{ s} \]

PF \(~5\%\) (0.5-1.7 keV)

*Pires et al. in prep.*
Spin Period Evolution

RX J0720.4-3125
Models for constant dP/dt
RX J1856.5-3754

Kaplan & van Kerkwijk 2005a
Kaplan & van Kerkwijk 2005b
van Kerkwijk & Kaplan 2008

RBS 1223
Spin Period Evolution

Kaplan & van Kerkwijk 2011

Kaplan & van Kerkwijk 2009b

Kaplan & van Kerkwijk 2009a
### Magnetic fields

**Magnetic dipole braking**  \( \rightarrow B_{\text{dip}} = 3.2 \times 10^{19} (P \cdot \frac{dP}{dt})^{1/2} \)

\[ \tau_{\text{char}} = \frac{P}{2(dP/dt)} \]

<table>
<thead>
<tr>
<th>Object</th>
<th>P [s]</th>
<th>( \frac{dP}{dt} ) [10(^{-13}) ss(^{-1})]</th>
<th>( \tau_{\text{char}} ) [Myr]</th>
<th>( B_{\text{dip}} ) [10(^{13}) G]</th>
<th>Ref.</th>
<th>Kinematic Age [Myr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RX J0420.0–5022</td>
<td>3.45</td>
<td>0.28(3)</td>
<td>2.0</td>
<td>1.0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>RX J0720.4–3125</td>
<td>8.39</td>
<td>0.698(2)</td>
<td>1.9</td>
<td>2.4</td>
<td>2</td>
<td>0.85</td>
</tr>
<tr>
<td>RX J0806.4–4123</td>
<td>11.37</td>
<td>0.55(30)</td>
<td>3.3</td>
<td>2.5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>1RXS J1308.8+2127</td>
<td>10.31</td>
<td>1.120(3)</td>
<td>1.5</td>
<td>3.4</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>RX J1605.3+3249</td>
<td>3.39</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RX J1856.5–3754</td>
<td>7.06</td>
<td>0.297(7)</td>
<td>3.8</td>
<td>1.5</td>
<td>5</td>
<td>0.46</td>
</tr>
<tr>
<td>1RXS J2143.0+0654</td>
<td>9.43</td>
<td>0.4(2)</td>
<td>3.7</td>
<td>2.0</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

XMM-Newton observations of the M7: absorption features

RX J0720.4–3125 variable with pulse phase and over years

Haberl et al. (2004), Hohle et al. (2012)

RBS 1223
EW = 150 eV
Pulse phase variations
Haberl et al. (2003)

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)

EPIC-pn: evidence for multiple lines
RX J1605.3+3249: Evidence for multiple lines

- **Black-body: \( \chi^2 = 4.38 \)**
- **1 Gaussian: \( \chi^2 = 2.39 \)**
- **2 Gaussian: \( \chi^2 = 1.75 \)**
- **3 Gaussian: \( \chi^2 = 1.39 \)**
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 2007, Ap&SS 308, 191

In any case $B \approx 10^{13} - 10^{14}$ G
Magnetic fields II

Unique opportunity to estimate $B$ in two independent ways:
- Magnetic dipole braking ($P, \frac{dP}{dt}$)
- Proton cyclotron absorption $\Rightarrow B = 1.6 \cdot 10^{11} \frac{E(\text{eV})}{(1 - 2GM/c^2R)^{1/2}}$

<table>
<thead>
<tr>
<th>Object</th>
<th>$P$</th>
<th>$B_{\text{dip}}$</th>
<th>$E_{\text{cyc}}$</th>
<th>$B_{\text{cyc}}$</th>
<th>$B_{\text{cyc}}/B_{\text{dip}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RX J0420.0–5022</td>
<td>3.45</td>
<td>1.0</td>
<td>?</td>
<td>5.6</td>
<td>2.3</td>
</tr>
<tr>
<td>RX J0720.4–3125</td>
<td>8.39</td>
<td>2.4</td>
<td>280</td>
<td>8.6/6.1</td>
<td>2.4-3.4</td>
</tr>
<tr>
<td>RX J0806.4–4123</td>
<td>11.37</td>
<td>2.5</td>
<td>430/306</td>
<td>6.0/4.6</td>
<td>1.4-1.8</td>
</tr>
<tr>
<td>1RXS J1308.8+2127</td>
<td>10.31</td>
<td>3.4</td>
<td>300/230</td>
<td>9/8</td>
<td></td>
</tr>
<tr>
<td>RX J1605.3+3249</td>
<td>3.39</td>
<td>450/400</td>
<td></td>
<td>9/8</td>
<td></td>
</tr>
<tr>
<td>RX J1856.5–3754</td>
<td>7.06</td>
<td>1.5</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>1RXS J2143.0+0654</td>
<td>9.43</td>
<td>2.0</td>
<td>750</td>
<td>15</td>
<td>7.5</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
Pulsars

high-energy detections (incomplete)

AXPs / SGRs (magnetars)

Magnificent Seven:
circles: \( \frac{P}{\dot{P}} \)
diamonds: cyclotron lines

magnetic dipole braking: age = \( \frac{P}{2\dot{P}} \), \( B = 3.2 \cdot 10^{19} (P\dot{P})^{1/2} \)
Neutron star birth places – kinematic ages

Motch et al. 2007, Ap&SS 308, 217:
Blue lines indicate possible INS positions assuming distances (unless better known) between 100 and 400 pc.
Red boxes show positions of OB associations.
RXJ1856: Upper Sco OB2
RXJ0720: Tr 10 + Vela OB2
RXJ1605: Upper Sco OB2

Tetzlaff et al. 2011:
RXJ1856: Upper Sco
0.46 ± 0.05 Myr
RXJ0720: Trumpler 10
0.85 ± 0.15 Myr
runaway star HIP 43158
→ current distance
286 ±27/-23 pc
Cooling of magnetized neutron stars

Strong magnetic fields: effects on
• the surface temperature distribution
• the thermal evolution

More information on magnetic fields is needed!
Spectral variations with pulse phase

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

RX J0420.0-5022  
Haberl et al. (2005)

RX J0806.4-4123
RX J0720.4–3125 pulse phase spectral variations

13–05–2000 (rev 0078)

06–11–2002 (rev 0530)

22–05–2004 (rev 0815)

12–11–2005 (rev 1086)
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
Phase shift in hardness ratios
varying phase lag between soft and hard emission?

Precession of the neutron star?

de Vries et al. (2004)
RX J0720.4–3125: Spectral variations, the first 5.5 years with XMM-Newton

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

<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: $280 \pm 6$ eV
common line width: $\sigma = 90 \pm 5$ 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

Haberl et al. 2006 A&A 451, L17
The continued spectral and temporal evolution of RX J0720.4–3125

No cyclic variations in spectral parameters with period < 12 years

$kT$ approaches constant value higher than before “event”

The “event” is not sudden

Phase residuals are energy dependent.

Phase lag between soft and hard X-ray emission varies on long term time scale.

Soft and hard emission originates from different locations. Two hot spots with somewhat different emission characteristics ($kT$, size, $B$?). Non-cyclic movement of spots?

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 $\sim 10^{31–32}$ erg s$^{-1}$
- Constant X-ray flux on time scales of years
- No obvious association with SNR
- No (faint?) radio emission (RBS1223, RBS1774)
- All are X-ray pulsars (3.39 – 11.37 s)
- Proper Motion is inconsistent with heating by accretion from ISM

<table>
<thead>
<tr>
<th>Object</th>
<th>T/$10^6$ K</th>
<th>kT/eV</th>
<th>P/s</th>
<th>Optical</th>
<th>distance/pc</th>
<th>$F_x$/cgs</th>
<th>$L_x$/cgs</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>(300–370)</td>
<td>3.3·10$^{-13}$</td>
<td>4.4·10$^{30}$</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>280 +210/–85</td>
<td>9.7·10$^{-12}$</td>
<td>7.9·10$^{31}$</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>(210–275)</td>
<td>2.4·10$^{-12}$</td>
<td>1.7·10$^{31}$</td>
</tr>
<tr>
<td>RX J1308.8+2127*</td>
<td>1.00</td>
<td>86</td>
<td>10.31</td>
<td>m$_{50ccd}$ = 28.6</td>
<td></td>
<td>3.2·10$^{-12}$</td>
<td>9.6·10$^{31}$</td>
</tr>
<tr>
<td>RX J1605.3+3249</td>
<td>1.11</td>
<td>96</td>
<td>3.39</td>
<td>B = 27.2</td>
<td>(300–415)</td>
<td>6.1·10$^{-12}$</td>
<td>9.4·10$^{31}$</td>
</tr>
<tr>
<td>RX J1856.5–3754</td>
<td>0.73</td>
<td>62</td>
<td>7.06</td>
<td>B = 25.2</td>
<td>123 +11/–15</td>
<td>1.3·10$^{-11}$</td>
<td>2.3·10$^{31}$</td>
</tr>
<tr>
<td>RX J2143.0+0654**</td>
<td>1.17</td>
<td>102</td>
<td>9.44</td>
<td>B = 27.4</td>
<td>(365–455)</td>
<td>2.8·10$^{-12}$</td>
<td>5.6·10$^{31}$</td>
</tr>
</tbody>
</table>

*1RXS J130848.6+212708 = RBS1223 (assumed d=500 pc)  ** 1RXS J214303.7+065419 = RBS 1774

Flux and Luminosity for 0.1-2.4 keV
Conclusions

• The idealized picture of a neutron star with uniform surface temperature and dipolar magnetic field is too simple.
• Strong magnetic fields
  influence surface temperature distribution (hot poles – asymmetries)
  change thermal evolution (cooling models)
  field decay?
• We need to better understand our systematic errors
  ages, distances
• We need to better understand the thermal emission from neutron stars
  neutron star atmosphere (condensation?)