Exploring the Surface of Isolated Neutron Stars with XMM-Newton

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Thermally emitting isolated neutron stars
- Surface temperature distributions
- Magnetic fields

XMM-Newton 10th Anniversary
ESAC, Villafranca del Castillo, Madrid, Spain
10th December 2009
Some history

1932  James Chadwick  
      Discovery of neutron (Nobel Prize in Physics 1935)

1931  Lew Landau  
      Proposal for the existence of neutron stars

1933  Walter Baade and Fritz Zwicky  
      Neutron stars as end products of stellar evolution created in supernova explosion  
      \[ p + e^- + 0.78 \text{ MeV} \rightarrow n + \nu_e \]

1939  Robert Oppenheimer and George Volkoff  
      Theoretical model for a neutron star  
      10 km radius, nuclear density – 10^9 tons per cm^{-3}

1967  Jocelyn Bell and Antony Hewish  
      Discovery of radio pulsars  
      rotation-powered

1971  Riccardo Giacconi et al.  
      Discovery of X-ray binary pulsar Cen X-3  
      powered by accretion of matter from companion star
Can we see isolated neutron stars directly?

expected size: 10 km radius
neutron star @ 100 pc ↔ dust particle (1μm) on Moon

expected surface temperature: Million degrees (100 eV)
$L = A \sigma T^4$
maximum radiation in soft X-ray band
inhomogeneous temperature distribution → pulsations

RX J0720.4-3125

Optical

RX J1856.5-3754

XMM-Newton

Chandra

X-rays
Thermally emitting neutron stars

- Cooling by neutrino emission from interior and photon emission from surface
- Temperatures inferred from X-ray spectra (atmosphere models, blackbody fits)
- Ages from pulsar spin-down timescales or kinematic ages from proper motions
Thermally emitting neutron stars

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Modelling of NS cooling:
- EOS
- Superfluid properties
- Stellar mass
- Envelope composition

Page et al. 2004
(ApJS 155, 623)
Middle-aged pulsars: The Three Musketeers

- First X-ray detections with Einstein Observatory
- Timing and spectral analysis with ROSAT
- ROSAT + ASCA: Three-component model

<table>
<thead>
<tr>
<th>P (ms)</th>
<th>dP/dt (ss⁻¹)</th>
<th>P/(2P) (years)</th>
<th>B (10¹² G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>385</td>
<td>5.50x10⁻¹⁴</td>
<td>111000</td>
<td>4.66</td>
</tr>
<tr>
<td>197</td>
<td>5.83x10⁻¹⁵</td>
<td>535000</td>
<td>1.09</td>
</tr>
<tr>
<td>237</td>
<td>1.10x10⁻¹⁴</td>
<td>342000</td>
<td>1.63</td>
</tr>
</tbody>
</table>

Cool BB (bulk of the star surface)
Hot BB (smaller hot spots)
Powerlaw (magnetosphere)

- XMM-Newton: Pulse phase spectroscopy

Middle-aged pulsars: The Three Musketeers

PSR B0656+14

Geminga

PSR B1055-52

Cool blackbody
Hot blackbody
Powerlaw

Challenge for the simple model based on centered dipole geometry
Radio-quiet isolated neutron stars: The Magnificent Seven

- Blackbody-like soft X-ray spectra
- No non-thermal hard X-ray emission
- No radio emission
- Proper Motion is inconsistent with heating by accretion from ISM
- Low ISM absorption ↔ nearby
- Probably all are X-ray pulsars (~10s)

Best cases 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>
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</thead>
<tbody>
<tr>
<td>RX J0420.0–5022</td>
<td>0.51</td>
<td>44</td>
<td>3.45</td>
<td>B &gt; 27.5</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_50ccd = 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>
</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>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 = 27.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

RX J1308.8+2127 = 1RXS J130848.6+212708 = RBS1223
RX J2143.0+0654 = 1RXS J214303.7+065419 = RBS 1774
The X-ray spectrum of RX J1856.5–3754

Black-body fit
No absorption features!

Counts $s^{-1}$ keV$^{-1}$
Counts $s^{-1}$ cm$^{-2}$ keV$^{-1}$
Photons $s^{-1}$ cm$^{-2}$ keV$^{-1}$

Photon Energy (keV)

$\begin{align*}
    n_H &= (9.5 \pm 0.03) \cdot 10^{19} \text{ cm} \\
    kT_\infty &= 63.5 \pm 0.2 \text{ eV} \\
    R_\infty &= 5.9 \pm 0.15 \text{ km (160pc)} \\
    L_{bol} &= 7.3 \cdot 10^{31} \text{ erg s}^{-1}
\end{align*}$

*Burwitz et al. (2003, 2004)*

Spectrum constant over time scales of years
Spectral variations with pulse phase: RBS 1223

Pulse phase spectroscopy

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

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

offset \( \sim 20^\circ \)

Schwope et al. (2005)

Two spots with different parameters and not antipodal!
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

XMM-Newton RGS

Precession of the neutron star?

de Vries et al. (2004)
RX J0720.4-3125 spectral variations
with pulse phase and on time scales of years
RX J0720.4-3125: A precessing neutron star?

Hohle et al. in preparation

\[ \chi^2_{\text{red}} = 9.05; \quad P_{\text{res}} = (7.26 \pm 0.18) \text{ yrs} \]

abs(sin): \[ \chi^2_{\text{red}} = 8.32; \quad P_{\text{res}} = (14.41 \pm 0.30) \text{ yrs} \]
XMM-Newton observations of the M7: absorption features

RBS 1223
EW = 150 eV
Variations of line parameters with pulse phase

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

Proton cyclotron absorption line?
Atomic line transitions?

In any case
B \approx 10^{13} – 10^{14} G

RX J1605.3+3249
E_{\text{line}} \approx 450 eV
Van Kerkwijk et al. (2004)

EPIC-pn:
evidence for multiple lines

van Kerkwijk & Kaplan 2007
Ap&SS 308, 191
### Summary - Magnetic fields

- **Magnetic dipole braking** \( \rightarrow B = 3.2 \cdot 10^{19} (P \cdot dP/dt)^{1/2} \)
- **Proton cyclotron absorption** \( \rightarrow B = 1.6 \cdot 10^{11} E(eV)/(1–2GM/c^2R)^{1/2} \)

<table>
<thead>
<tr>
<th>Object</th>
<th>P [s]</th>
<th>Semi Amplitude</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>
</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>0.55(30)</td>
<td>430/306(^a))</td>
<td>2.5</td>
<td>8.6/6.1</td>
</tr>
<tr>
<td>RX 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></td>
<td>9/8</td>
</tr>
<tr>
<td>RX J1856.5–3754</td>
<td>7.06</td>
<td>1.5%</td>
<td>0.30(7)</td>
<td></td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>RX J2143.0+0654</td>
<td>9.43</td>
<td>4%</td>
<td>0.41(18)</td>
<td>750</td>
<td>2.0</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
Cooling of strongly magnetized neutron stars

Strong effects of magnetic field on
- heat transport → surface temperature distribution
- the thermal evolution

- Geminga
- PSR B1055
- PSR B0656
- RX J0720
- RBS 1223
- RX J1856

Spin-down age $P/(2dP/dt)$ overestimates true age

RX J1856:
kinematic age much shorter
Summary and outlook

Isolated cooling neutron stars
   The Three Musketeers
       $\tau \approx 10^{5-6}$ years, $B \approx (1-5) \times 10^6$ G (dipole braking)
   The Magnificent Seven
       a few $10^6$ years from $dP/dt$, younger from kinematic ages
       $10^{13}$ G (dP/dt + absorption features, factor of 2-3 difference)
Influence of the magnetic field on
   surface temperature distribution
   thermal evolution

The idealized picture of a neutron star with uniform surface temperature and dipolar magnetic field is too simple.

Stability of XMM-Newton instruments
Further monitoring of RX J0720.4–3125: Periodic behaviour?
Period evolution of M7 stars: Relation $B_{db} \leftrightarrow B_{cyc}$