Accreted highly magnetized neutron stars: recent progress

Alexander Lutovinov

S.Tsygankov, S.Molkov
A.Mushtukov, V.Suleimanov
A.Shtykovskiy, J.Poutanen
Current observational situation

Observatories and instruments in orbit: Chandra, XMM-Newton, Swift, INTEGRAL, Fermi/GBM, NuSTAR, NICER, MAXI

Timing capabilities: from $\sim 10^{-5}$ to $10^8$ sec

Spectral ranges: $\sim 0.5 – 200$ keV

Luminosities: from $10^{32}$ to $10^{40}$ erg/s

High sensitivity and flexibility (regular, TOO, monitoring)

Swift/XRT monitoring campaign: more than dozen sources, total exposure $> 1$ Msec, hundreds observations
Propeller effect

Absorbed power-law
Gamma = 0.4 – 0.7

Black body with
kT = 0.5 keV

Tsygankov et al., 2016
Lutovinov et al., 2017
Propeller effect

$L_{\text{Bol}}$ vs. $P$, erg cm$^{-2}$ s$^{-1}$

$\dot{P}$, s/s

Flux (bolometric), erg cm$^{-2}$ s$^{-1}$

Time, MJD

$B \simeq (3.5 - 4.5) \times 10^{12}$ G

$D \sim 18$ kpc

$Lutovinov et al., 2019$

will appear 15/01 in astro-ph
Accretion from the cold disk

\[ L_{\text{lim}}(R) \sim \frac{G M \dot{M}_{\text{lim}}}{R} \sim 4 \times 10^{37} \xi^{7/2} B_{12}^2 P^{-7/3} M_{1.4}^{-2/3} R_6^5 \text{ erg s}^{-1} \]

\[ L_{\text{cold}} = 9 \times 10^{33} k^{1.5} M_{1.4}^{0.28} R_6^{1.57} B_{12}^{0.86} \text{ erg s}^{-1} \]

\[ P^* = 36.6 k^{6/7} B_{12}^{0.49} M_{1.4}^{-0.17} R_6^{1.22} \text{ s} \]

Tsygankov et al., 2017a
Long period pulsars

transition to the cold disk at the luminosity around $10^{35}$ erg/s

$E_{\text{cyc}} \approx 42.8$ keV

Similar to XPer

Di Salvo et al. 1998

Tsygankov et al., 2018b
Highly magnetized neutron star in very low states
Motivations and aims

Insights into the problem of the accretion on to magnetized neutron star at very low mass accretion rates

Study cooling of NSs

VFXTs
LMXBs
Very weak MF

Wijnands et al. 2013
Motivations and aims

Insights into the problem of the accretion on to magnetized neutron star at very low mass accretion rates

Cooling of the NSs with magnetic field

Geppert et al. 2006
BeXRB systems (snapshot obs)

<table>
<thead>
<tr>
<th>Source name</th>
<th>Pulse period (s)</th>
<th>Orbital period (d)</th>
<th>Distance (kpc)</th>
<th>Cyclotron line (keV)</th>
<th>Optical companion</th>
</tr>
</thead>
<tbody>
<tr>
<td>4U 0115+63</td>
<td>3.6</td>
<td>24.3</td>
<td>7.0</td>
<td>11.5</td>
<td>B0.2Ve</td>
</tr>
<tr>
<td>V 0332+53</td>
<td>4.375</td>
<td>34.25</td>
<td>7.0</td>
<td>28.6</td>
<td>O8–9Ve</td>
</tr>
<tr>
<td>MXB 0656–072</td>
<td>160.4</td>
<td>101.2</td>
<td>3.9</td>
<td>36.9</td>
<td>O9.7Ve</td>
</tr>
<tr>
<td>4U 0728–25</td>
<td>103</td>
<td>34.5</td>
<td>6.1</td>
<td>–</td>
<td>O8–9Ve</td>
</tr>
<tr>
<td>RX J0812.4–3114</td>
<td>31.9</td>
<td>81.3</td>
<td>9.2</td>
<td>–</td>
<td>B0.5V–IIIe</td>
</tr>
<tr>
<td>GS 0834–430</td>
<td>12.3</td>
<td>105.8</td>
<td>5.0</td>
<td>–</td>
<td>B0–2 V–IIIe</td>
</tr>
<tr>
<td>GRO J1008–57</td>
<td>93.8</td>
<td>249.5</td>
<td>5.8</td>
<td>88</td>
<td>B0e</td>
</tr>
<tr>
<td>2S 1417–624</td>
<td>17.6</td>
<td>42.1</td>
<td>(1.4–11.1)</td>
<td>–</td>
<td>B1 Ve</td>
</tr>
<tr>
<td>2S 1553–542</td>
<td>9.3</td>
<td>30.6</td>
<td>20</td>
<td>23.5</td>
<td>–</td>
</tr>
<tr>
<td>Swift J1626.6–5156</td>
<td>15.377</td>
<td>132.9</td>
<td>10</td>
<td>10</td>
<td>B0Ve</td>
</tr>
<tr>
<td>GS 1843+00</td>
<td>29.5</td>
<td>–</td>
<td>(10–15)</td>
<td>20</td>
<td>B0–B2IV–Ve</td>
</tr>
<tr>
<td>XTE J1946+274</td>
<td>15.8</td>
<td>169.2</td>
<td>(8–10)</td>
<td>36</td>
<td>B0–B1 IV–Ve</td>
</tr>
<tr>
<td>KS 1947+300</td>
<td>18.8</td>
<td>40.4</td>
<td>10</td>
<td>12.5</td>
<td>B0Ve</td>
</tr>
<tr>
<td>SAX J2103.5+4545</td>
<td>351</td>
<td>12.7</td>
<td>6.5</td>
<td>–</td>
<td>B0Ve</td>
</tr>
<tr>
<td>Cep X-4</td>
<td>66.3</td>
<td>21</td>
<td>3.8</td>
<td>30</td>
<td>B1V–B2Ve</td>
</tr>
<tr>
<td>SAX J2239.3+6116</td>
<td>1247</td>
<td>262</td>
<td>4.4</td>
<td>–</td>
<td>(B0–2 V–IIIe)</td>
</tr>
</tbody>
</table>

Special program of observations with Chandra
Also: using available XMM and XRT data
Long term history based on Swift/BAT and ASM/RXTE data

Tsygankov et al., 2017c
Spectra (I)

3 yr, 0.3 keV  
$6 \times 10^{32}$ erg/s

>5 yr, 0.4 keV  
$3 \times 10^{32}$ erg/s

4 yr, 1 keV  
$4 \times 10^{33}$ erg/s

No OB, PL  
$1.2 \times 10^{34}$ erg/s

No OB, 0.1 keV  
$1.6 \times 10^{33}$ erg/s

<1 yr, ~2 keV  
$3 \times 10^{32}$ erg/s  
non-thermal

4 m after type II  
2 w after type I  
PL, $9 \times 10^{34}$ erg/s

3.3 yr, PL  
$3 \times 10^{33}$ erg/s
Spectra (II)

5yr, 0.7 keV
1x10^{33} erg/s

3 and 7yr, PL
0.4-1.7x10^{34} erg/s

3yr, few phs
2x10^{33} erg/s

2yr, PL
10^{34} erg/s

9 m, PL
4.5x10^{34} erg/s

<1 yr, ~1 keV or
PL 1.2
2x10^{33} erg/s

4 yr, PL
2x10^{33} erg/s

No OB,
PL or BB???
1.1x10^{33} erg/s
Observational conclusions

The whole sample of sources can be roughly divided into two distinct groups:

(i) relatively bright objects with a luminosity around $10^{34}$ erg s$^{-1}$ and (hard) power-law spectra (4U0728-25, GROJ1008-57, SwiftJ1626.6-5156, XTEJ1946+274, KS1947+300, several possible candidates)

X-ray pulsations were detected from five objects in group (i) with quite a large pulse fraction of 50–70 per cent.

(ii) fainter ones showing thermal spectra (4U0115+63, V0332+53, MXB0656-072, RXJ0812.4-3114)

BUT! There is no correlation between the emission temperature and time after the last outburst, i.e. we don’t’ see cooling directly. WHY?
Emission in the very low state can be originated and contaminated by different factors

- Leakage of matter through the centrifugal barrier
- Magnetospheric accretion
- Thermal emission from the cooling NS
- Coronal activity of the companion star

\[ T_{\text{keV}}(r = R_m) \simeq 0.03 B_{12}^{-3/7} L_{37}^{13/28}. \]
Origin of the very low emission of NSs

- Thermal emission from the cooling NS:

The matter accumulated during outbursts compresses the original NS crust and enriches it with low-Z elements.

It leads to non-equilibrium reactions (electron captures, neutron emissions, pycnonuclear reactions).

Most of this heat is conducted inwards to the core, but a small part is radiated from the NS surface as thermal photons

“Deep crustal heating” model  \(\text{Brown et al., 1998}\)

\[
L_q \approx 6 \times 10^{32} \text{ ergs s}^{-1} (\langle \dot{M} \rangle/10^{-11} \text{ M}_\odot \text{ yr}^{-1}),
\]

\(\text{Rutledge et al., 2007}\)
<table>
<thead>
<tr>
<th>Source</th>
<th>Period (s)</th>
<th>$L_{prop}(R)$ (10^{33} \text{ erg s}^{-1})</th>
<th>$\langle \dot{M} \rangle$ (10^{-10} \text{ M}_\odot \text{ yr}^{-1})</th>
<th>$L_q$ (10^{33} \text{ erg s}^{-1})</th>
<th>$L_{bb}$ (10^{33} \text{ erg s}^{-1})</th>
<th>$L_{pl}$ (10^{33} \text{ erg s}^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>4U 0115+63</td>
<td></td>
<td>174</td>
<td>0.7</td>
<td>4.3</td>
<td>$0.59^{+0.07}_{-0.06}$</td>
<td>$1.14^{+0.20}_{-0.15}$</td>
</tr>
<tr>
<td>V 0332+53</td>
<td></td>
<td>991</td>
<td>1.0</td>
<td>5.5</td>
<td>$0.26^{+0.06}_{-0.06}$</td>
<td>$0.54^{+0.16}_{-0.08}$</td>
</tr>
<tr>
<td>V 0332+53 (XMM)</td>
<td></td>
<td>991</td>
<td>1.0</td>
<td>5.5</td>
<td>$0.34^{+0.04}_{-0.04}$</td>
<td>$0.59^{+0.09}_{-0.08}$</td>
</tr>
<tr>
<td>MXB 0656–072</td>
<td></td>
<td>0.3</td>
<td>0.2</td>
<td>1.3</td>
<td>$3.80^{+0.27}_{-0.25}$</td>
<td>$5.62^{+0.40}_{-0.38}$</td>
</tr>
<tr>
<td>4U 0728–25 (XRT aver)</td>
<td></td>
<td>g</td>
<td>0.2</td>
<td>1.3</td>
<td>$7.91^{+0.57}_{-0.52}$</td>
<td>$11.2^{+0.3}_{-0.3}$</td>
</tr>
<tr>
<td>RX J0812.4–3114</td>
<td></td>
<td>g</td>
<td>0.4</td>
<td>2.2</td>
<td>$1.60^{+0.82}_{-0.62}$</td>
<td>$2.54^{+1.58}_{-1.05}$</td>
</tr>
<tr>
<td>GS 0834–430</td>
<td></td>
<td>g</td>
<td>0.3</td>
<td>1.9</td>
<td>$0.27^{+0.29}_{-0.12}$</td>
<td>$0.37^{+0.27}_{-0.16}$</td>
</tr>
<tr>
<td>GRO J1008–57</td>
<td></td>
<td>5.5</td>
<td>1.0</td>
<td>5.6</td>
<td>$66.8^{+1.4}_{-1.3}$</td>
<td>$94.3^{+2.2}_{-2.1}$</td>
</tr>
<tr>
<td>2S 1417–624</td>
<td></td>
<td>g</td>
<td>0.3</td>
<td>2.1</td>
<td>$2.01^{+0.40}_{-0.38}$</td>
<td>$2.66^{+0.54}_{-0.40}$</td>
</tr>
<tr>
<td>2S 1553–542</td>
<td></td>
<td>119</td>
<td>1.5</td>
<td>8.8</td>
<td>$1.05^{+0.44}_{-0.65}$</td>
<td>$2.24^{+0.90}_{-0.85}$</td>
</tr>
<tr>
<td>Swift J1626.6–5156 (10049)</td>
<td>15.3360(6)</td>
<td>5.9</td>
<td>0.7</td>
<td>4.3</td>
<td>$12.5^{+0.6}_{-0.5}$</td>
<td>$17.3^{+0.9}_{-0.8}$</td>
</tr>
<tr>
<td>Swift J1626.6–5156 (14642)</td>
<td></td>
<td>5.9</td>
<td>0.7</td>
<td>4.3</td>
<td>$2.87^{+0.66}_{-0.66}$</td>
<td>$4.15^{+0.81}_{-0.70}$</td>
</tr>
<tr>
<td>GS 1845+00</td>
<td></td>
<td>5.1</td>
<td>1.2</td>
<td>7.3</td>
<td>$1.55^{+1.34}_{-0.66}$</td>
<td>$2.00^{+1.32}_{-0.77}$</td>
</tr>
<tr>
<td>XTE J1946+274</td>
<td></td>
<td>15.760(3)</td>
<td>67</td>
<td>0.3</td>
<td>$8.06^{+0.78}_{-0.71}$</td>
<td>$11.6^{+1.1}_{-1.0}$</td>
</tr>
<tr>
<td>KS 1947+300</td>
<td></td>
<td>18.802(3)</td>
<td>3.7</td>
<td>1.8</td>
<td>$32.9^{+1.4}_{-1.1}$</td>
<td>$46.5^{+3.3}_{-2.5}$</td>
</tr>
<tr>
<td>SAX J21035+4545</td>
<td></td>
<td>350.7(1.1)</td>
<td>g</td>
<td>0.5</td>
<td>$1.49^{+0.22}_{-0.16}$</td>
<td>$2.42^{+0.36}_{-0.31}$</td>
</tr>
<tr>
<td>Cep X-4</td>
<td></td>
<td>66.38(3)</td>
<td>1.7</td>
<td>0.05</td>
<td>$1.22^{+0.15}_{-0.15}$</td>
<td>$1.94^{+0.21}_{-0.19}$</td>
</tr>
<tr>
<td>SAX J2239.3+6116</td>
<td></td>
<td>g</td>
<td>0.06</td>
<td>0.4</td>
<td>$1.01^{+0.29}_{-0.23}$</td>
<td>$1.46^{+0.34}_{-0.27}$</td>
</tr>
</tbody>
</table>

\[
L_{prop}(R) = \frac{GM\dot{M}_{prop}}{R} \\
\approx 4 \times 10^{37} k^{7/2} B_{12}^2 P^{-7/3} M_{1.4}^{-2/3} R_6^5 \text{ erg s}^{-1}
\]

\[
L_q = \left( \langle \dot{M} \rangle/10^{-11} \text{ M}_\odot \text{ yr}^{-1} \right) \times 6 \times 10^{32} \text{ erg s}^{-1}
\]
Cooling in 4U0115+63

Wijnands, Degenaar 2016, Ruoco Escorial et al. 2017
Conclusions

• Strong progress in the study of highly magnetized neutron stars in last years

• Direct detection of the propeller effect

• New paradigm of the cold accretion disk

• First systematic study of Be systems in quiescent state to study cooling of NS with a strong magnetic fields