The quiescent X-ray emission of AXPs and SGRs – powered by accretion from a fallback disk

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-- Fall-Back Disk Model
-- Accretion Geometry, Spectral Formation & Beaming
-- Radio emission from AXPs/SGRs
-- Summary & Conclusions

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Two basic models for
Anomalous X-ray Pulsars and Soft Gamma Ray Repeaters

The classical magnetar model (Thompson ...):
Large and giant bursts: decay of magnetic fields: $B \sim 10^{14-15}$ G
magnetic dipole braking: $P \frac{dP}{dt} B_d \sim 10^{14-15}$ G
quiescent luminosity $L_x \gg \frac{dE_{\text{rot}}}{dt}$: $L_x$ is powered by magnetic field decay

Braking and powering by accretion from a fall-back disk (Alpar ...)
Large and giant bursts: decay of multipole magnetic fields: $B \sim 10^{14-15}$ G
braking by disk-magnetosphere interaction $B_d \sim 10^{12-13}$ G
quiescent luminosity: $L_x \gg \frac{dE_{\text{rot}}}{dt}$: $L_x$ is powered by accretion

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History of accretion models for AXPs/SGRs

1995 van Paradijs + AXPs are single neutron stars accreting from a residual disk are remnants from the common-envelope evolution of an HXM

2000 Chatterjee +
2001 Alpar AXPs accrete from a supernova fall-back disk

followed by a series of papers of the Istanbul group 2003 – 2011 on the disk physics and disk-magnetosphere interaction

showing that the required neutron star dipole fields are $10^{12} – 10^{13}$ G and the masses of the disks are $10^{-5} – 10^{-4}$ $M_\odot$

and explaining the period clustering of AXPs & SGRs at $P = 2-12$ s

the IR/optical radiation from 4U 0142+61 (Wang + 2006) and from 1E 2259+586 (Kaplan + 2009)

the low magnetic field of SGR 0418+5729 (Rea + 2010)
(Alpar + 2011)
the braking index of $n = 0.9$ of PSR J1734-3333 (Espinoza + 2011)
(Caliskan + 2012, submitted)

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The persistent emission is produced by accretion from a fall-back disk by bulk motion comptonization (BMC) & thermal comptonization (TC).

4U 0142 +61:
- $B \sim 10^{13}$ G
- $P = 9.1$ s
- $r_A \sim 10^9$ cm

$h(\text{disk}) \sim 10^7$ cm

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BMC/TC fit to the spectrum of AXP 4U 0142+61

The best fit BMC & TC model fitted to Chandra MEG/HEG & Integral ISGRI data

< 10 keV: photospheric spectrum: blackbody-like
+ TC power law (thermal comptonization)
> 10 keV: BMC power law (bulk motion comptonization)

(Truemper, Zezas, Ertan & Kylafis A&A 2010)
AXPs/SGRs spectra have two components

Suzaku spectra
(Enoto + 2010)

Two spectral components

$L_{\text{hard}}/L_{\text{soft}} \approx 1 \pm \text{factor 3}$

In general two pulses per period

soft emission from the polar cap

origin of the hard tail?

4U 0142+61
Double component spectrum:
Thermal & bulk motion
Comptonization (Truemper + 2010)
The two component X-ray spectrum

Soft part: Thermal Comptonization and blackbody

Hard tail: Bulk motion Comptonization (BMC)

e.g. Lyubarski & Sunyaev (1982) Becker & Wolff (2007)

Schematic view of the emission region

infalling electrons
E \sim \text{50 - 100 keV}

radiative shock

polar cap photosphere
kT_e = 0.42 \text{ keV}, R_{pc} \sim 8\text{km}

polar beam:
scattered + thermal photons

fan beam:
BMC + TC photons
optimum \tau_t \sim 5

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Modeling the energy dependent pulse profiles
phase dependent spectra

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The full pulse profiles (including the dc component) of 4U 0142+61
derived from the data of den Hartog + 2008 by Dennerl & Truemper

main pulse (0.8 – 160 keV)
peaking at phase 1.1
„fan beam“

secondary pulse (0.8 – 80 keV)
peaking at phase 0.6
„polar beam“

symmetric/asymmetric pulse profiles
Modelling the fan beam and polar beam

-- in the absence of firm theoretical predictions for the angular distribution of fan beams from accretion columns and of the absorption & reflection of the fan beam by the photosphere

we take a pragmatic approach by assuming beaming functions, e.g. Leahy (1991):

\[ I(\theta) \sim \sin^m \theta \quad \text{for the fan beam emitted by the accretion column} \]
\[ \sim \cos^n \theta \quad \text{for the polar beam,} \]
\[ (n = 1: \text{blackbody emission}) \]

-- we treat the gravitational bending using the formula of Beloborodov (2002) and

-- calculate the illumination of the polar cap by the fan beam using the work of Leahy (2003)

-- we assume \( M = 1.4 \, M_\odot \) and \( R = 12.5 \, \text{km} \) \( (R/R_\odot = 3) \)
Geometry of the accretion column

For an inclined dipole the Alfven surface is not circular in the plane of the accretion disk. The matter enters the magnetosphere not along the whole of the inner disk edge but in two opposite regions leading to a footprint as shown in the figure. (Basko & Sunyaev 1976, supported qualitatively by MHD simulations of Romanova + 2008, for much smaller magnetospheres).

This means there is an azimuthal modulation of the column width! In our model we describe that by an aspect ratio $q = d_o/l_o < 1$

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Motivated by the general view that for low luminosity sources the radiative shock is located close to the neutron star surface we start with a height $H = 0$.

The fits to the pulse profiles give the following parameters:

$i = 42.1 \pm 0.4$ degrees (inclination)

$\alpha = 19.0 \pm 0.9$ degrees (dipole / rotation axis)

$q = 0.69 \pm 0.03$

Our method yields the „intrinsic“ luminosities of the fan and polar beam:

$L_{\text{fan}} = 4.4 \times 10^{35}$ erg/s
for $H = 0$ about 50% hits the polar cap, viz. $\sim 2.2 \times 10^{35}$ erg/s

$L_{\text{polar}} = 0.7 \times 10^{35}$ erg/s

the albedo of the photosphere is $< 30\%$
and 70% disappears into the stellar interior

This seems unrealistic

Leahy (1991) fitted the pulse shapes of 20 accreting X-ray pulsars with

$m = 2 - 4$

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On the other hand the height of the shock depends on dM/dt and the radius of the column and may be at $H > 0$. In this case a smaller fraction of the fan beam hits the neutron star surface.

For $H = 2\text{km}$ the fits yield

$i = 59\text{ degrees}$

$\alpha = 30\text{ degrees}$

$q = 0.8$

$L(\text{fan}) = 1.8 \times 10^{35} \text{ erg/s}$

20% reaches the photosphere,

Viz. $3.6 \times 10^{34} \text{ erg/s}$

$L(\text{polar}) = 0.3 \times 10^{35} \text{ erg/s}$

$\rightarrow$ 75% photospheric albedo

We conclude that our model requires a height of the radiative shock of the order $H \sim 2 \text{ km}$

The $m$ and $n$ are in the range $(2-4)$ used by Leahy (1991) to fit the pulse profiles of 20 accreting X-ray pulsars

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Modelling the pulse shape distributions measured by den Hartog et al. 2008

\( H \) varied between 0 and 6.25 km

\( H = 2 \) km
\( i = 59 \) degrees
\( \alpha = 30 \) degrees
\( q = 0.8 \)

\( L(\text{fan}) = 1.8 \times 10^{35} \text{ erg/s} \)
20% reaches the photosphere,

Viz. \( 3.6 \times 10^{34} \text{ erg/s} \)

\( L(\text{polar}) = 3 \times 10^{34} \text{ erg/s} \)

\( \rightarrow \sim 80\% \) photospheric albedo

We conclude that our model requires a height of the radiative shock of the order \( H \sim 2 \) km

The \( m \) and \( n \) are in the range \((2 - 4)\) used by Leahy (1991) to fit the pulse profiles of 20 accreting X-ray pulsars

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The resulting geometry for $H = 2\,\text{km}$

M = 1.4 $M_\odot$
R = 12.5 km

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The line of sight swings between zenith angles of ~29° and ~89° degrees

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Phase dependent spectra of 4U 0142+61 (JT + 2010)

(data taken from den Hartog + 2008)

fan beam
BMC/TC photons

polar beam
BB + reflected photons

peak at 60 keV
(2.5σ)
enhanced scattering at the cyclotron resonance

B ~ 5 x 10^{12} (1+z) G

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Why do AXPs/SGRs have hard X-ray tails in contrast to binary X-ray pulsars having similar magnetic fields?

AXPs/SGRs are less luminous by a factor of ~ 100!

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There are two accreting X-ray pulsars in binary systems with low luminosities and strong magnetic fields

4U 0352+309 (X Per) \( L_x \sim 2.4 \times 10^{34} \text{ ergs}^{-1} \); \( B \sim 2.5 \times 10^{12} \text{ G} \)

4U 2206+54 average \( L_x \sim 1.5 \times 10^{35} \text{ ergs}^{-1} \); \( B \sim 3.3 \times 10^{12} \text{ G} \)

4U 0352+309 shows a hard tail with \( \Gamma \sim 2 \) at low luminosities \( (L_x \geq 10^{34} \text{ ergs}^{-1}) \)
Steep spectrum with \( \Gamma \sim 3 \) at high luminosities \( (L_x \sim 2.7 \times 10^{35} \text{ ergs}^{-1}) \)
(Reig + 2012)
## Comparison with Accreting X-ray Pulsars (schematic)

<table>
<thead>
<tr>
<th></th>
<th>Her X-1</th>
<th>AXP 4U 0142+61</th>
<th>X - Persei</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L_x) (erg/s)</td>
<td>(3 \times 10^{37})</td>
<td>(3 \times 10^{35})</td>
<td>(2.4 \times 10^{34})</td>
</tr>
<tr>
<td>(B_d) (G)</td>
<td>(4 \times 10^{12})</td>
<td>(5 \times 10^{12})</td>
<td>(2.5 \times 10^{12})</td>
</tr>
<tr>
<td>Cut-off (keV)</td>
<td>(~ 20) keV</td>
<td>(~1/1)</td>
<td>(&gt; 1)</td>
</tr>
<tr>
<td>Hard/soft</td>
<td>very low</td>
<td>(~ 1/1)</td>
<td>65</td>
</tr>
</tbody>
</table>

- BMC producing the hard tail takes place over the whole cross section
- The hard X-ray photons escape as a fan beam from an optical depths \(\tau_e\)
- optimum condition for the production of a hard tail: \(\tau_e \approx \tau_T\) (\(\approx 5\))

- blue regions: From them hard BMC photons do escape

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\[D \sim L^{1/7} B^{-2/7}\]

(Shapiro & Teukolsky 1983)
The XDINSs ("Magnificent Seven") have ages up to \( \sim 10^6 \) yrs and magnetic fields \( \geq 10^{13} \) G.

The AXPs/SGRs have ages up to \( \sim 10^4 \) yrs.

What is the relation between both classes?

AXPs/SGRs \( \rightarrow \) Mag 7?

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A possible coexistence of the radio and X-ray emission of AXPs/SGRs?
The radio emission of AXPs

Three of AXPs/SGRs have shown radio emission:

-- 1E 1547-54 , $P = 2.07$ s (Camilo et al. 2006)
-- XTE J1810-197, $P = 5.54$ s (Halpern et al. 2005)
-- PSR J1622-4950 $P = 4.33$ s (Levin et al. 2010)

For normal accreting neutron stars the radio emission is quenched. But for the AXPs/SGRs the situation may be different due to the low accretion rate and the long period:
The radio polar cap is small due to the long pulse period and may be separated from the accretion region allowing the co-existence of radio emission and accretion

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Summary and Conclusions

-- the „quiescent“ X-ray emission of SGRs and AXPs is powered by accretion
-- the dipole fields of these sources are $10^{12} - 10^{13}$ G
-- the super-Eddington bursts are produced by the decay of localized (multipole) magnetic fields of $10^{14} - 10^{15}$ G
-- the radio emission of AXPs may coexist with accretion

NB: Also in the sun the magnetic fields in activity regions are ~ 100 times larger than the solar dipole field!

„Accreting Magnetar“

Thank you!