

X-rays from Isolated Neutron Stars: The „Three Musketeers“ meet the „Magnificent Seven“

Frank Haberl

Max-Planck-Institut für extraterrestrische Physik (MPE), Garching

X-ray observations of thermally emitting isolated neutron stars

- Surface temperature distributions
- Magnetic fields
  - Pulse timing
  - Absorption features in the X-ray spectra

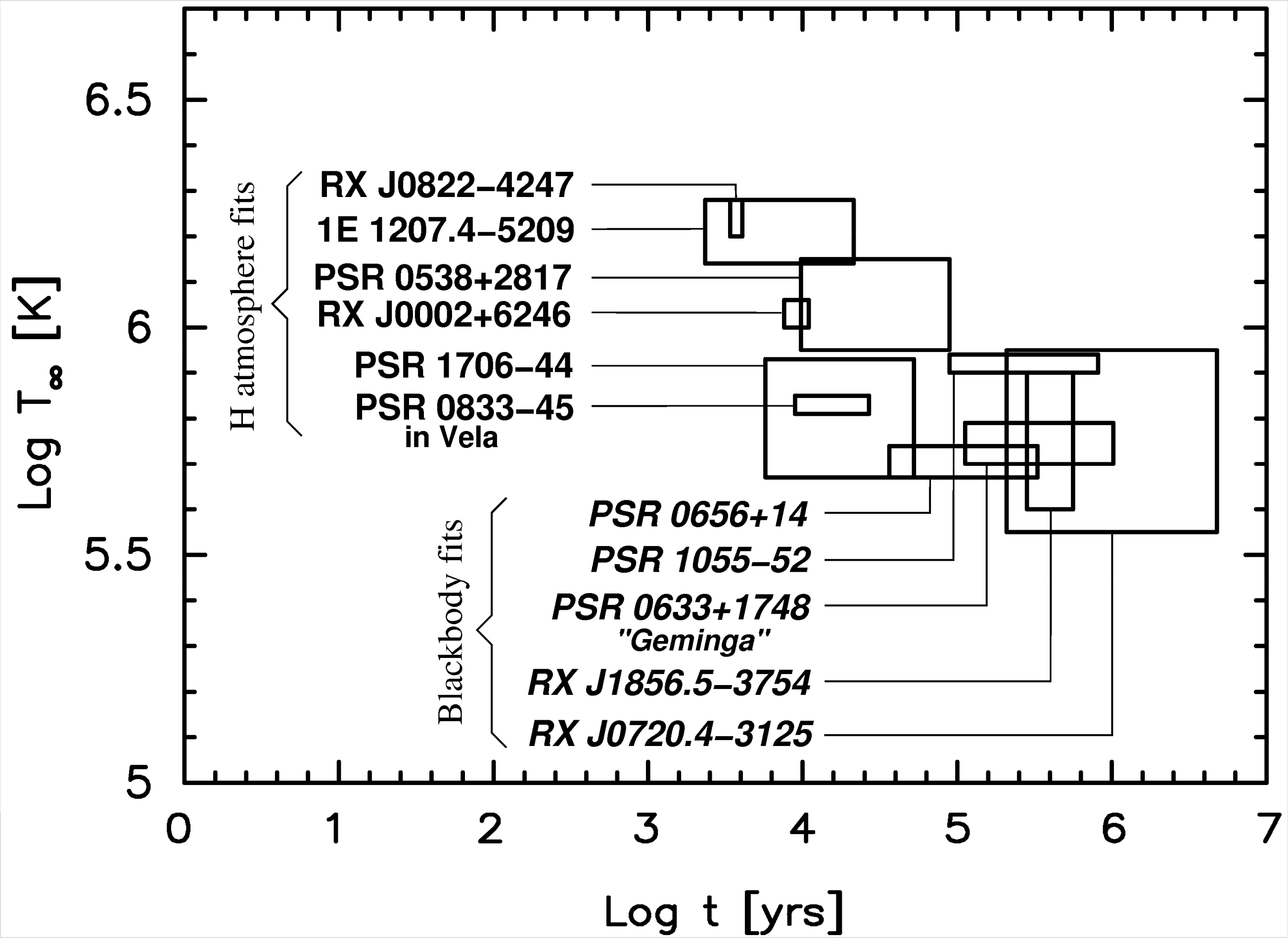
The case of RX J0720.4-3125

- Spectral variations on long-term time scales

The X-ray Universe 2008

Granada, Spain, 27-30 May 2008

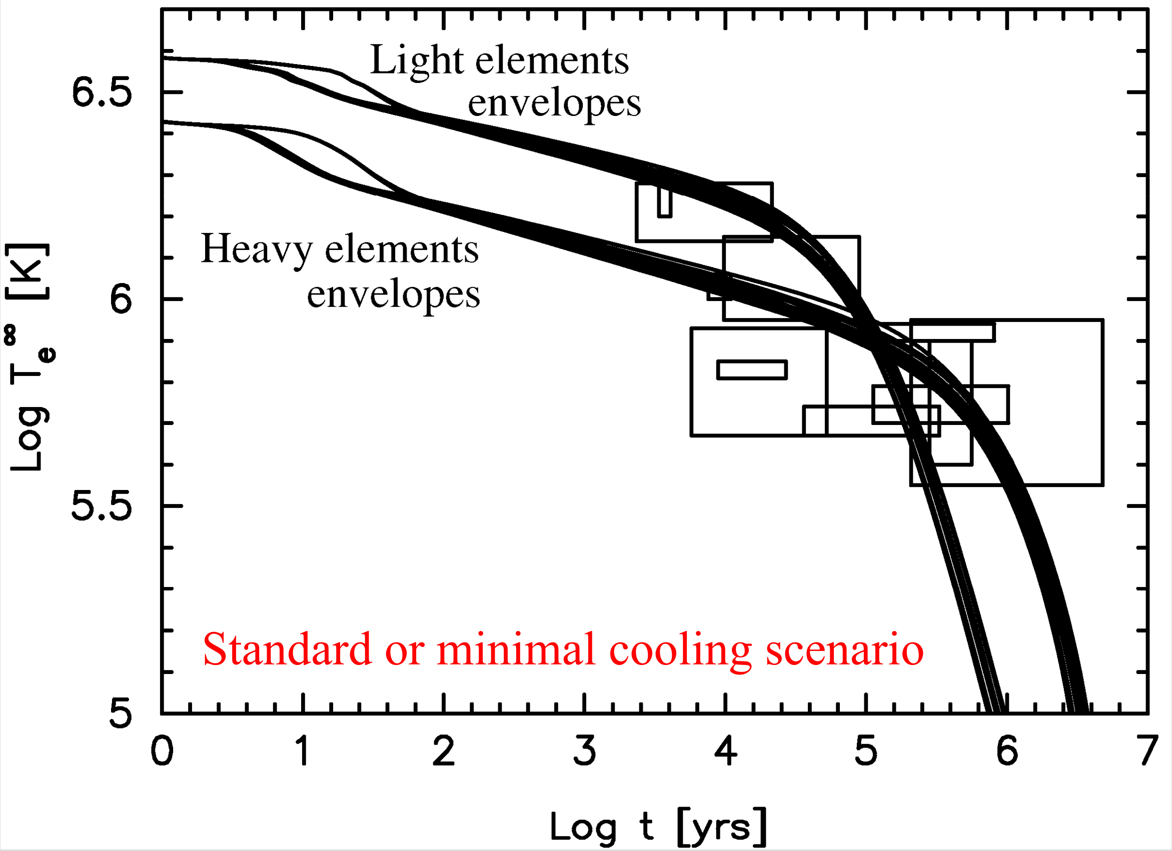
Thermally emitting neutron stars



Page et al. 2004 (ApJS 155, 623)

- 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

Cooling of neutron stars



- EOS
- Superfluid properties
- Stellar mass
- Envelope composition

Page et al. 2004
(ApJS 155, 623)

- Models assume spherically symmetric temperature distribution
- Observations cannot be explained by a unique temperature
  Pulsations in the X-ray flux
  Multi-component X-ray spectra
  Mismatch between X-ray spectra and optical band

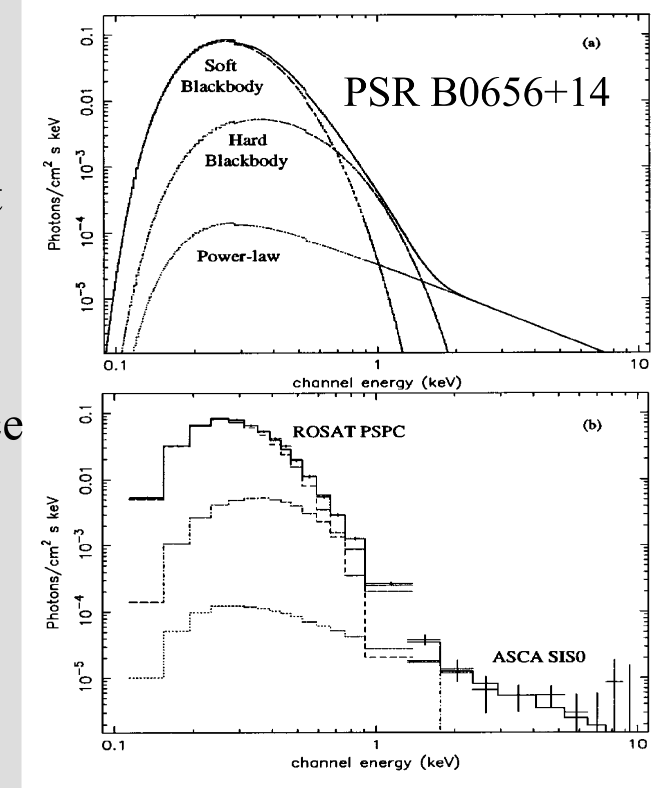
Middle-aged pulsars: The Three Musketeers

	P (ms)	dP/dt (ss^{-1})	$P/(2\dot{P})$ (years)	B (10^{12} G)	d (pc)
B0656+14	385	5.50×10^{-14}	111000	4.66	288
B1055-52	197	5.83×10^{-15}	535000	1.09	~750
Geminga	237	1.10×10^{-14}	342000	1.63	157 (250 +120/-62)

Faherty et al. 2007

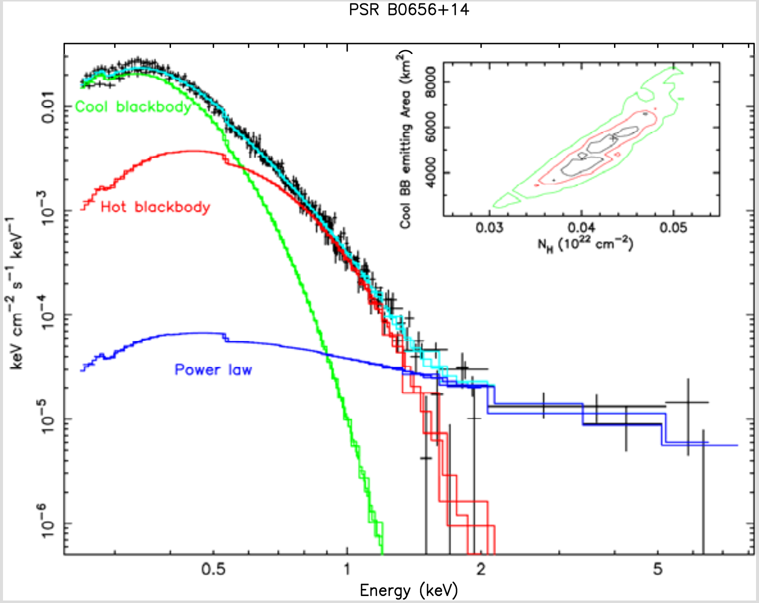
- First X-ray detections with Einstein Observatory
- Timing and spectral analysis with ROSAT
  - X-ray spectra dominated by thermal emission
  - two components, soft blackbody plus harder component

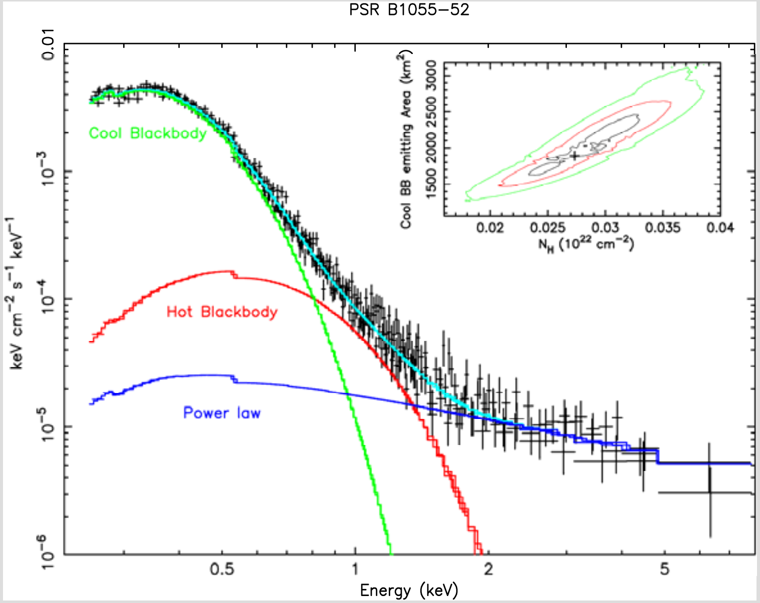
- ROSAT + ASCA:
  - Three-component model
    - Cool BB probably from the bulk of the star surface
    - Hot BB from a smaller hot spot
    - Powerlaw from the magnetosphere
- Chandra + XMM-Newton
  - Pulse phase spectroscopy
    - De Luca et al. 2005 (ApJ 623, 1051)



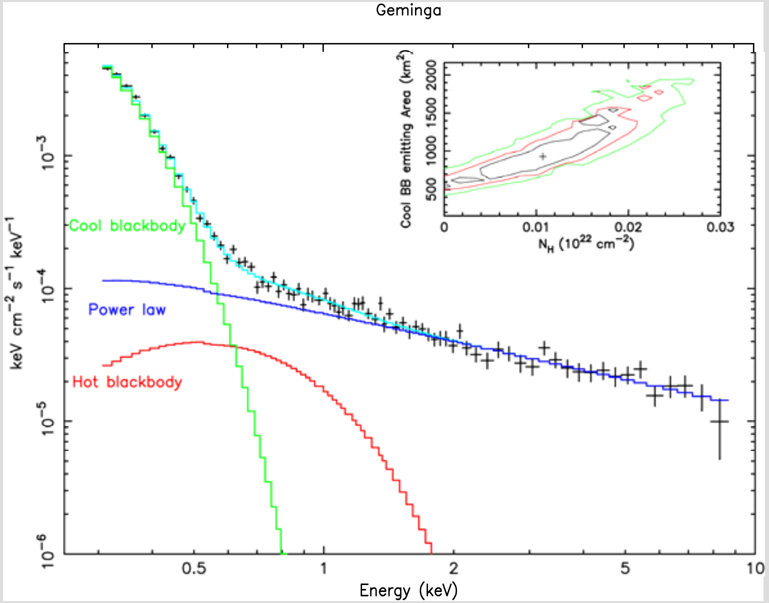
Greiveldinger et al. 1996

Middle-aged pulsars: The Three Musketeers





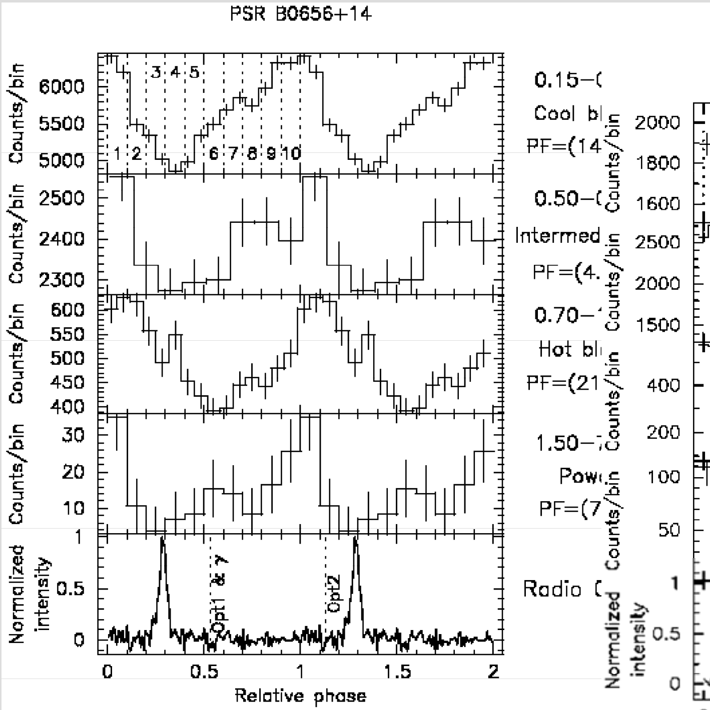
EPIC-pn
pulse averaged spectra

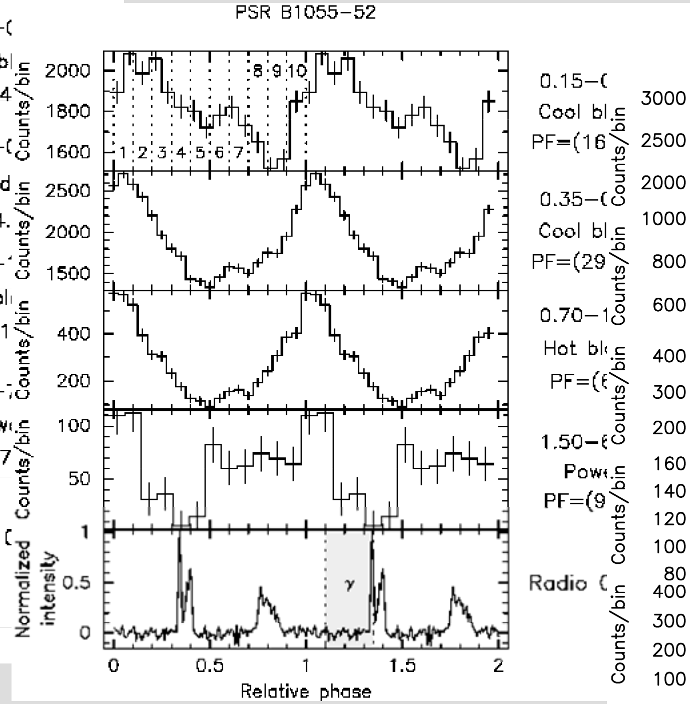


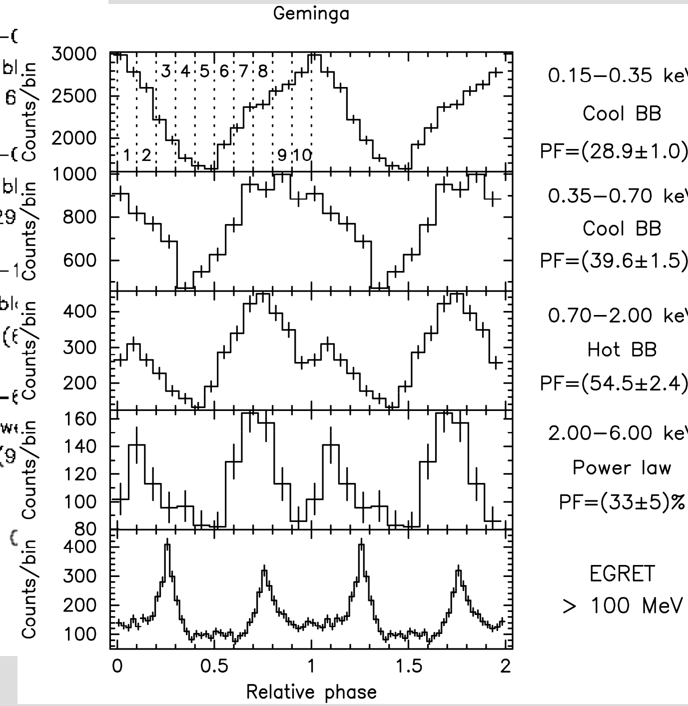
De Luca et al. 2005 (ApJ 623, 1051)

Middle-aged pulsars: The Three Musketeers

EPIC PN





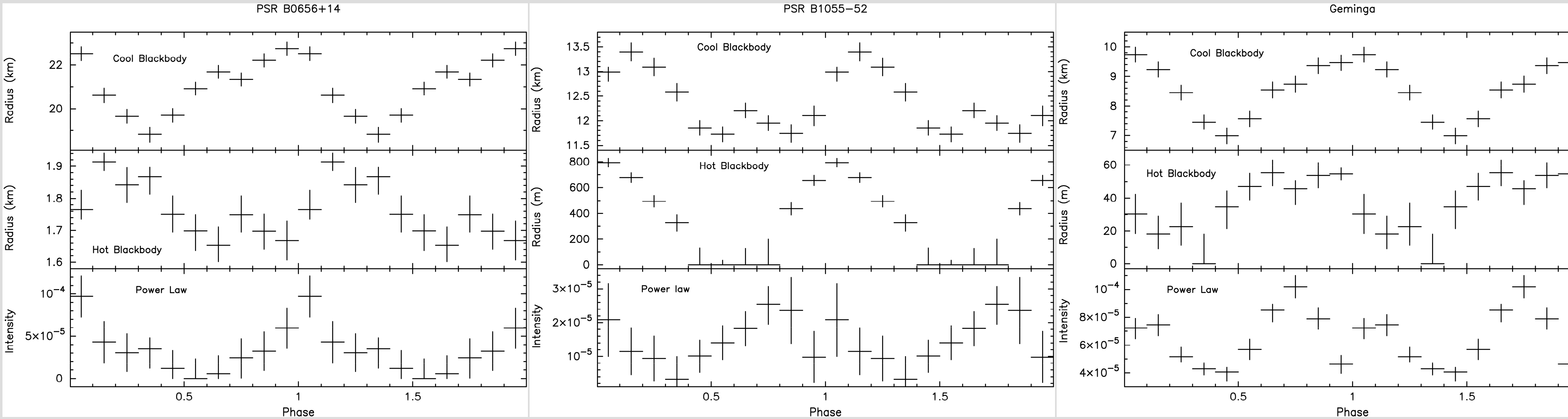


Pulse profiles in different energy bands

Pulse phase spectroscopy

De Luca et al. 2005 (ApJ 623, 1051)

Middle-aged pulsars: The Three Musketeers



large neutron star radius (d = 288 pc)
nH = (4.3 ± 0.2) x 10^{20} cm^{-2} (X-ray)
DM = 14.0 pc cm^{-3} (670 pc)
10% ionization -> nH = 4.3 x 10^{20} cm^{-2}

blackbody components vary in antiphase
shallow modulation
almost aligned rotator

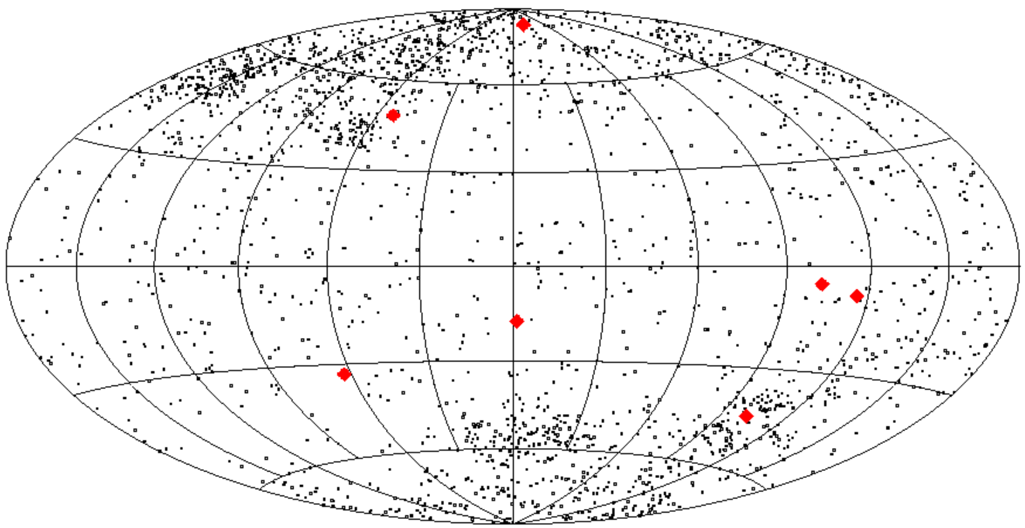
neutron star radius: uncertain distance (750 pc)
nH = (2.7 ± 0.2) x 10^{20} cm^{-2}
DM = 30.1 pc cm^{-3}
10% ionization -> nH ~ 9 x 10^{20} cm^{-2}
blackbody components vary in phase
strong modulation
hot spot disappears for 40% of pulse period
supports model of an orthogonal rotator
but only one pole?

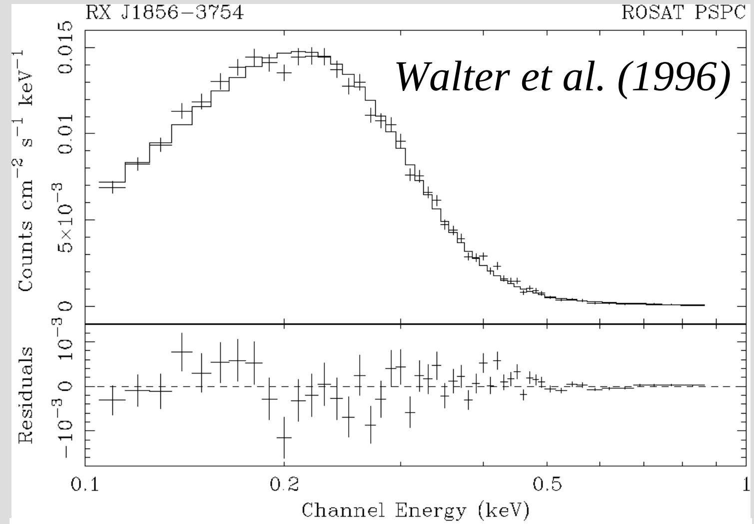
small neutron star radius for d = 157 pc
~12.7 (9.6 - 18.9) km
for d = 250 (188 - 370) pc

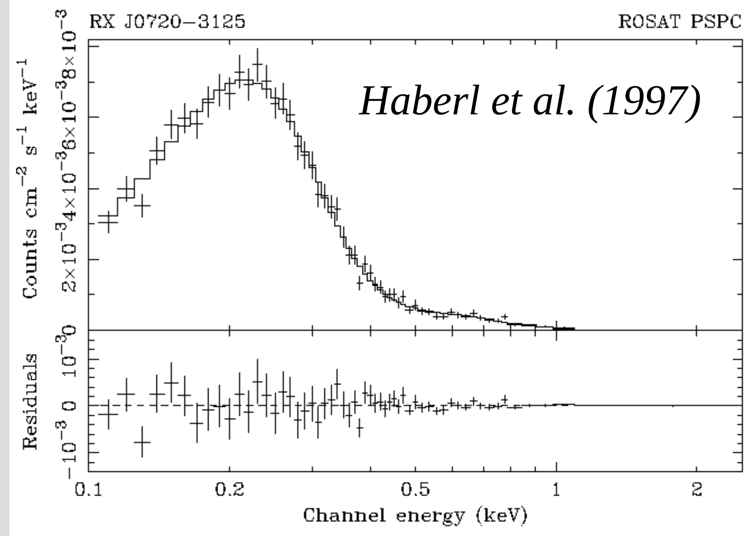
Challenge for the simple model based on centered dipole geometry

A Legacy of ROSAT: The discovery of seven radio-quiet neutron stars

Soft X-ray spectrum + faint in optical







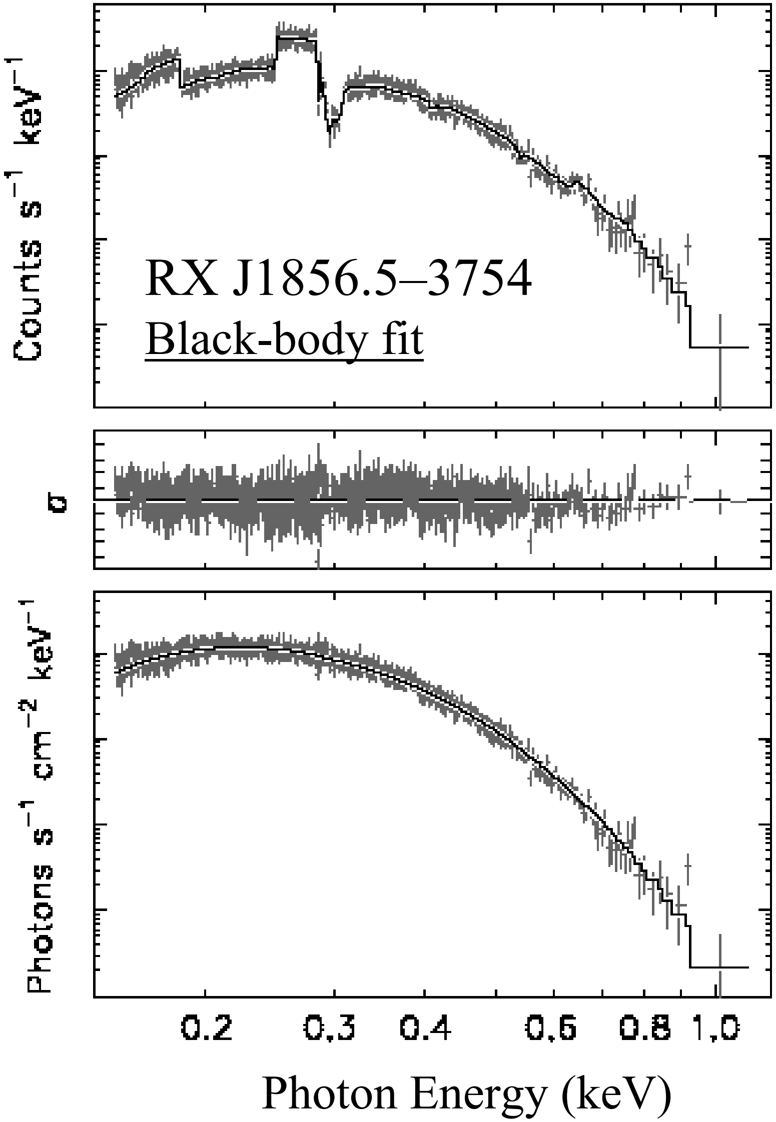
PSPC cts/s	HR1	HR2	Name
0.15 ± 0.01	-0.96 ± 0.03	-0.45 ± 0.73	RX J0420.0-5022
0.23 ± 0.03	-0.06 ± 0.12	-0.60 ± 0.17	RBS1774 = 1RXS J214303.7+065419
0.29 ± 0.02	-0.20 ± 0.08	-0.51 ± 0.11	RBS1223 = 1RXS J130848.6+212708
0.38 ± 0.03	-0.74 ± 0.02	-0.66 ± 0.08	RX J0806.4-4123
0.78 ± 0.02	-0.67 ± 0.02	-0.68 ± 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 undisturbed emission from stellar surface

The X-ray spectrum of RX J1856.5–3754

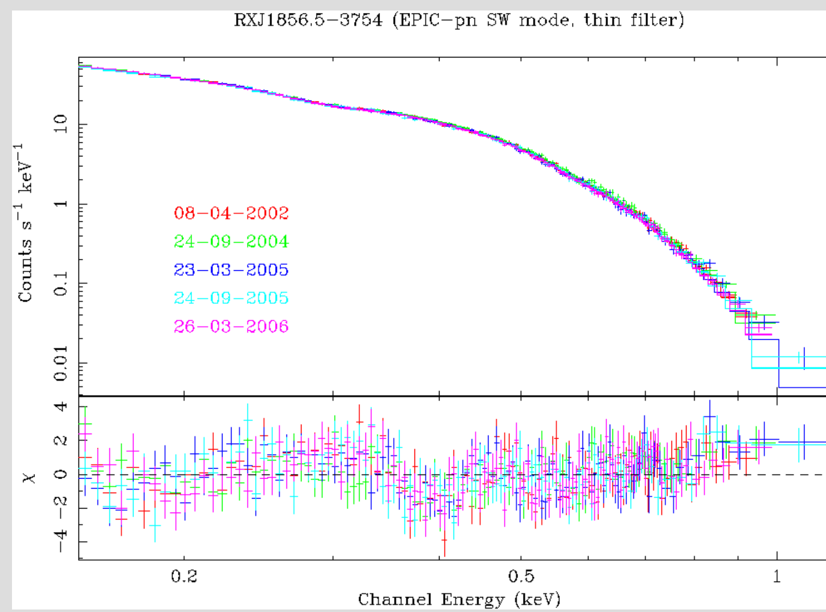
Chandra LETGS



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

No narrow absorption features !

Burwitz et al. (2003,2004)



XMM EPIC-pn

Spectrum constant over time scales of years

Haberl (2006)

Thermal, radio-quiet isolated neutron stars

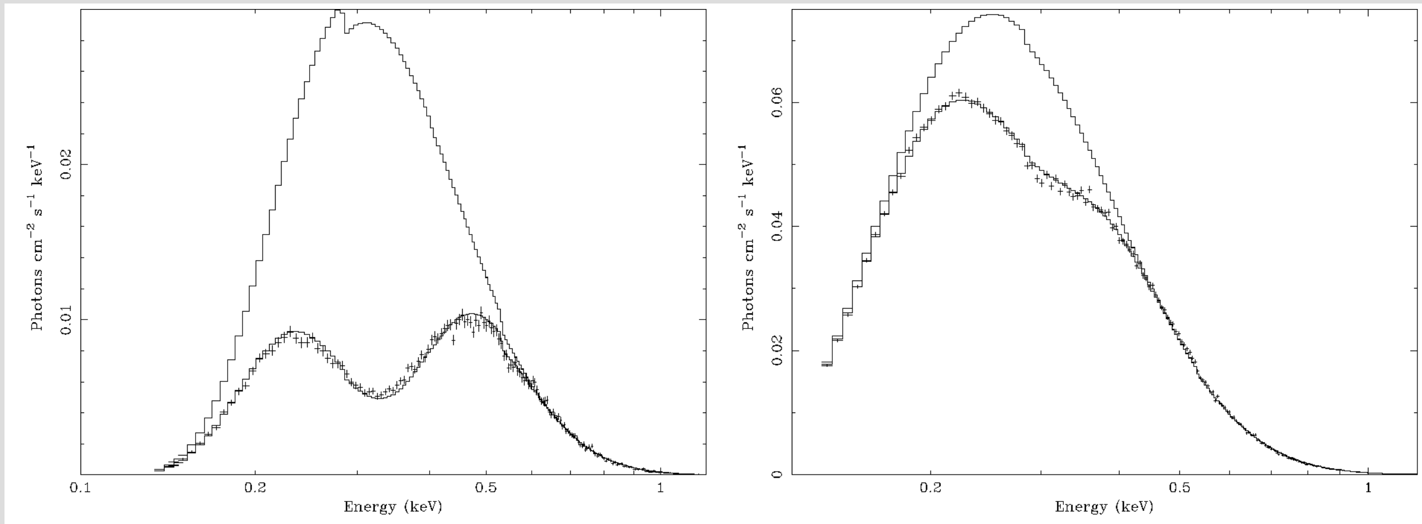
- Soft X-ray sources in ROSAT survey + optically faint → isolated neutron stars
- Blackbody-like X-ray spectra, NO non-thermal hard emission
- Low absorption ~10^{20} H cm^{-2} → nearby (2 cases with measured parallax)
- Luminosity ~10^{31} erg s^{-1}
- Constant X-ray flux on time scales of years
- No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

Object	$T/10^6$ K	kT/eV	P/s	Optical	PM/mas/y	distance/pc
RX J0420.0–5022	0.51	44	3.45	B = 26.6		
RX J0720.4–3125	0.99-1.10	85-95	8.39	B = 26.6	97	330 +170/-80
RX J0806.4–4123	1.11	96	11.37	B > 24		
RX J1308.8+2127*	1.00	86	10.31	m_{50ccd} = 28.6		
RX J1605.3+3249	1.11	96	6.88?	B = 27.2	145	
RX J1856.5–3754	0.73	62	7.06	B = 25.2	332	161 +18/-14
RX J2143.0+0654**	1.17	102	9.44	B = 27.4		

* 1RXS J130848.6+212708 = RBS1223 ** 1RXS J214303.7+065419 = RBS 1774

XMM-Newton observations of the M7: absorption features

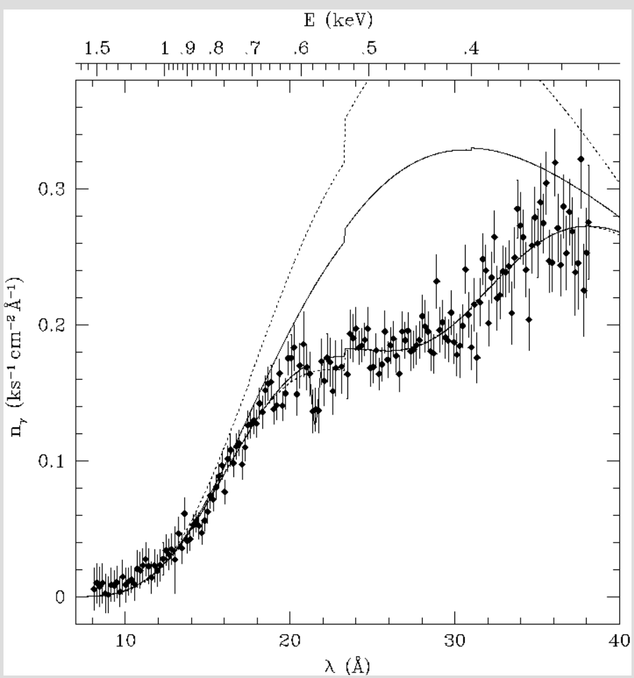
RBS 1223
EW = 150 eV
Pulse phase variations



XMM-Newton EPIC-pn

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

XMM-Newton RGS



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

The origin of the absorption features

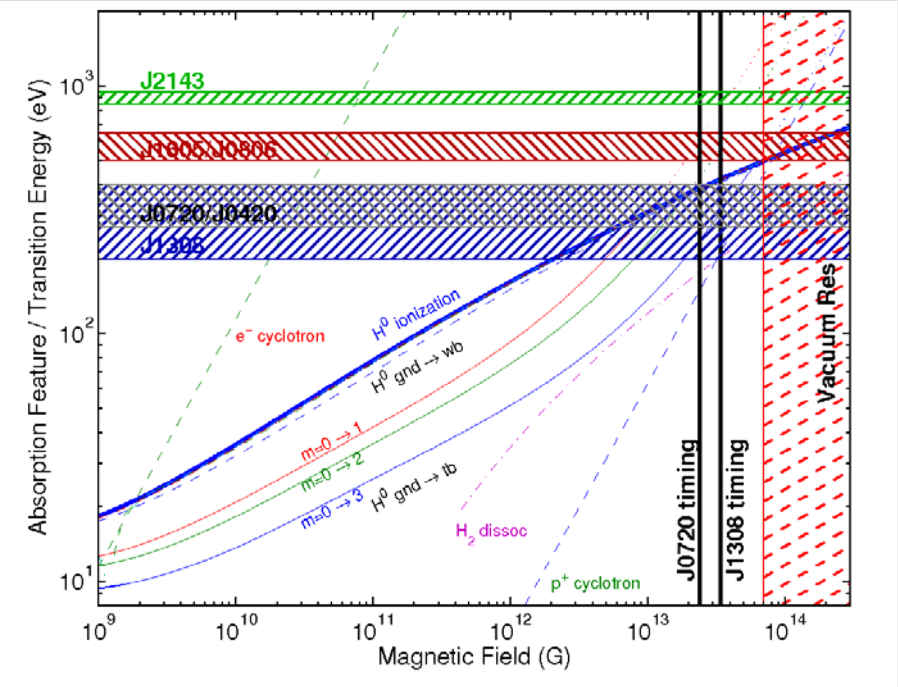
Proton cyclotron absorption line ?

In the case of proton scattering harmonics should be greatly suppressed.

Atomic line transitions ?

Hydrogen ?

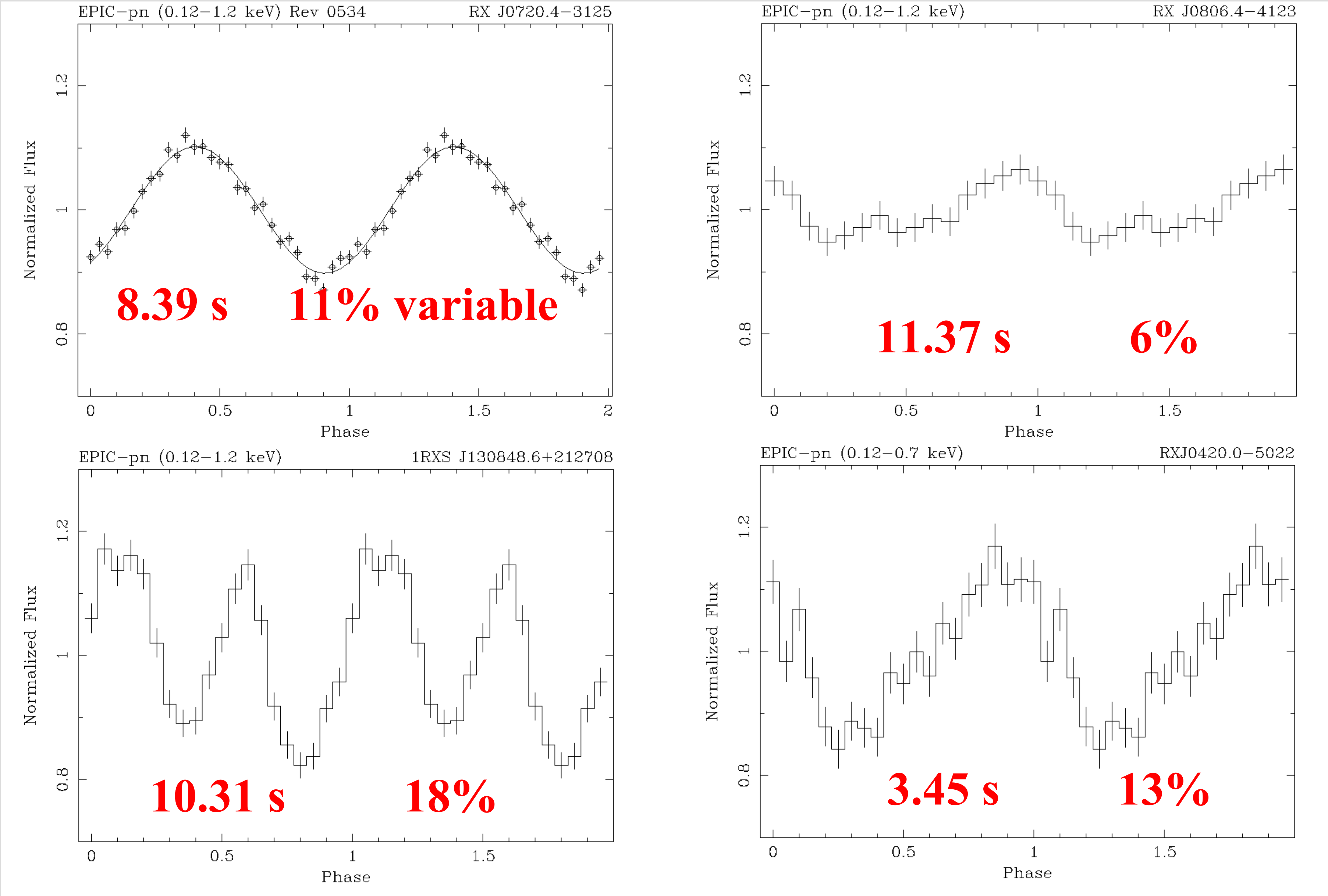
Mixture ?



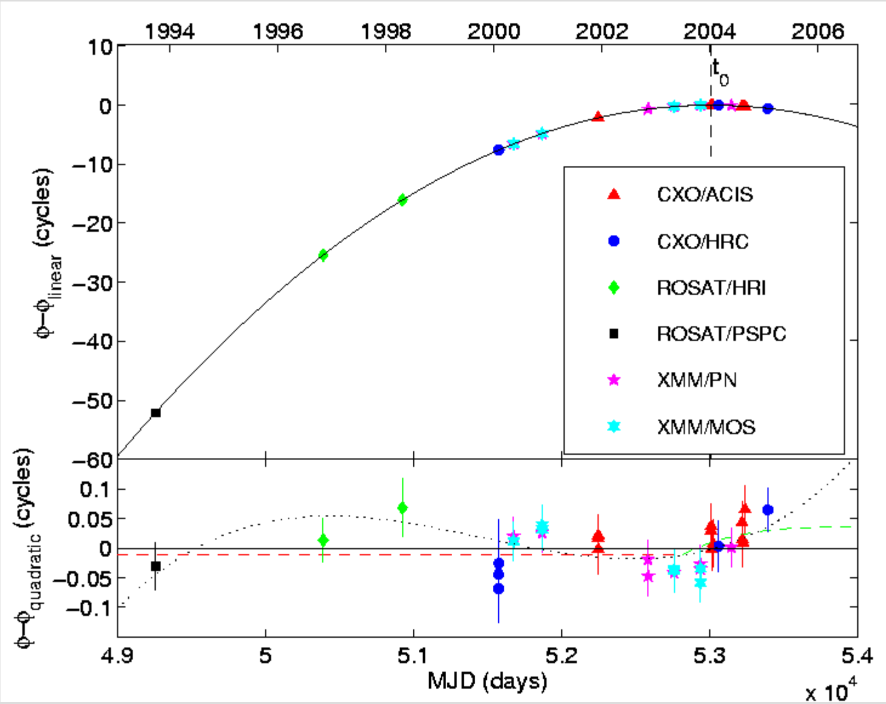
van Kerkwijk & Kaplan 2007, Ap&SS 308, 191

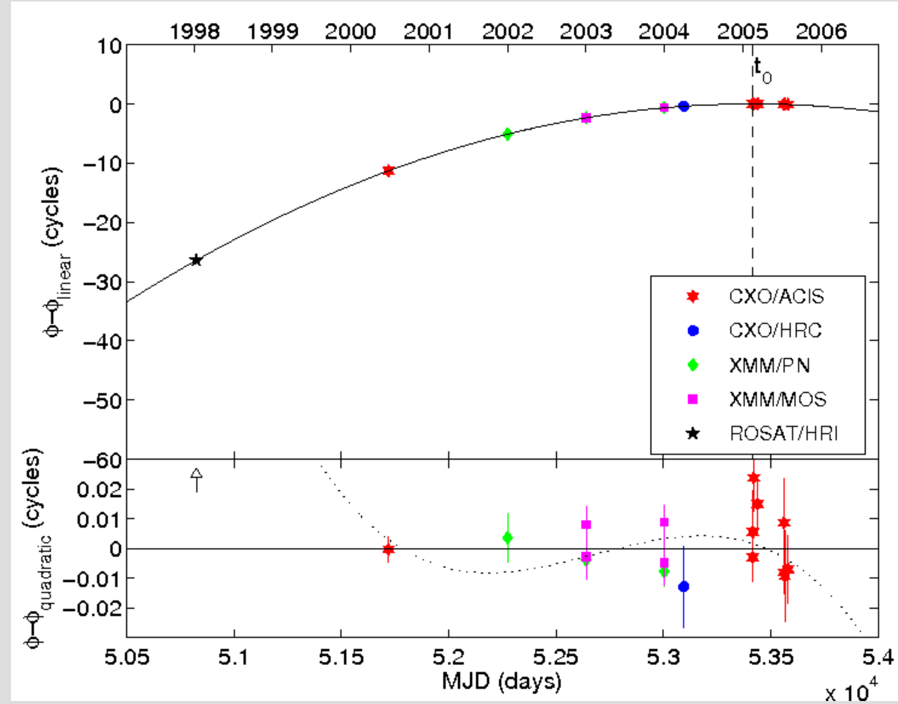
In any case B ≈ 10^{13} – 10^{14} G

X-ray pulsations



Period history: RX J0720.4–3125 and RBS 1223





$P = 8.39$ s

$dP/dt = (0.698 \pm 0.002) \cdot 10^{-13}$ s s^{-1}

$\tau = P/2(dP/dt) = 1.9 \cdot 10^6$ y

$B = 2.4 \cdot 10^{13}$ G

Kaplan & van Kerkwijk 2005
ApJ 628, L45

$P = 10.32$ s

$dP/dt = (1.120 \pm 0.003) \cdot 10^{-13}$ s s^{-1}

$\tau = P/2(dP/dt) = 1.5 \cdot 10^6$ y

$B = 3.4 \cdot 10^{13}$ G

Kaplan & van Kerkwijk 2005
ApJ 635, L65
van Kerkwijk et al. 2007
ApJ 659, L149

Magnetic fields

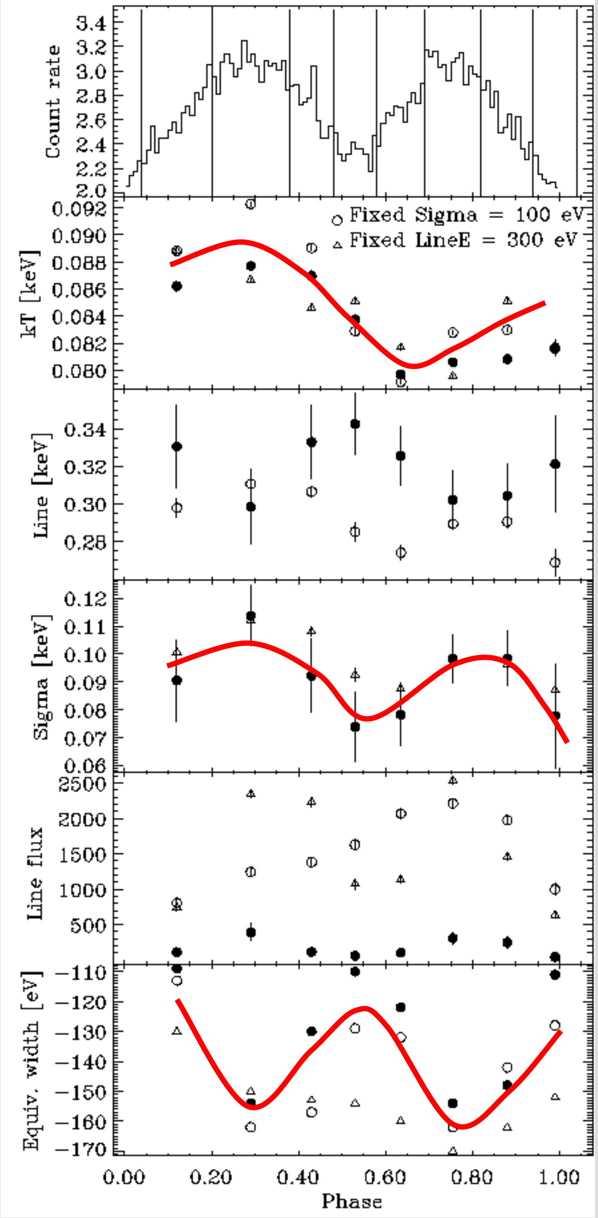
Unique opportunity to estimate B in two independent ways:

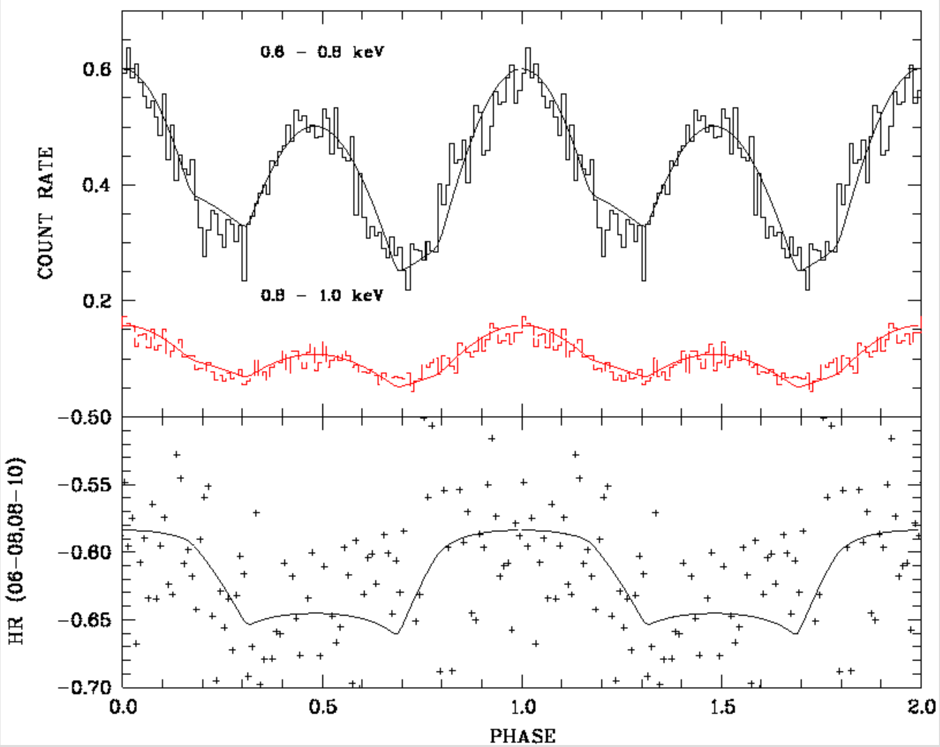
- **Magnetic dipole braking → $B = 3.2 \times 10^{19} (P \times dP/dt)^{1/2}$**
  Spin-down rate (P, dP/dt)
  (Spin-down luminosity required to power the Hα nebula (dE/dt, τ))
- **Proton cyclotron absorption → $B = 1.6 \times 10^{11} E(eV)/(1-2GM/c^2R)^{1/2}$**

Object	P [s]	Semi Ampl.	dP/dt [10^{-13} ss^{-1}]	E_{cyc} [eV]	B_{db} [10^{13} G]	B_{cyc} [10^{13} G]
RX J0420.0–5022	3.45	13%	< 92	?	< 18	
RX J0720.4–3125	8.39	8-15%	0.698(2)	280	2.4	5.6
RX J0806.4–4123	11.37	6%	< 18	430/306[a)]	< 14	8.6/6.1
1RXS J1308.8+2127	10.31	18%	1.120(3)	300/230[a)]	3.4	6.0/4.6
RX J1605.3+3249	6.88?			450/400[b)]		9/8
RX J1856.5–3754	7.06	1.5%	0.30(7)	–	1.4	–
1RXS J2143.0+0654	9.43	4%	<60[c)]	750	< 24	15

a) Spectral fit with single line / two lines
b) With single line / three lines at 400 eV, 600 eV and 800 eV
c) Radio detection: Malofeev et al. 2006, ATEL 798

Spectral variations with pulse phase: RBS 1223





RBS 1223 (10.31s) ***Schwope et al. 2005***

Two-spot model: $kT_{\infty} = 92$ **eV and 84 eV**

$2\Phi \sim 8^{o}$ **and** $\sim 10^{o}$

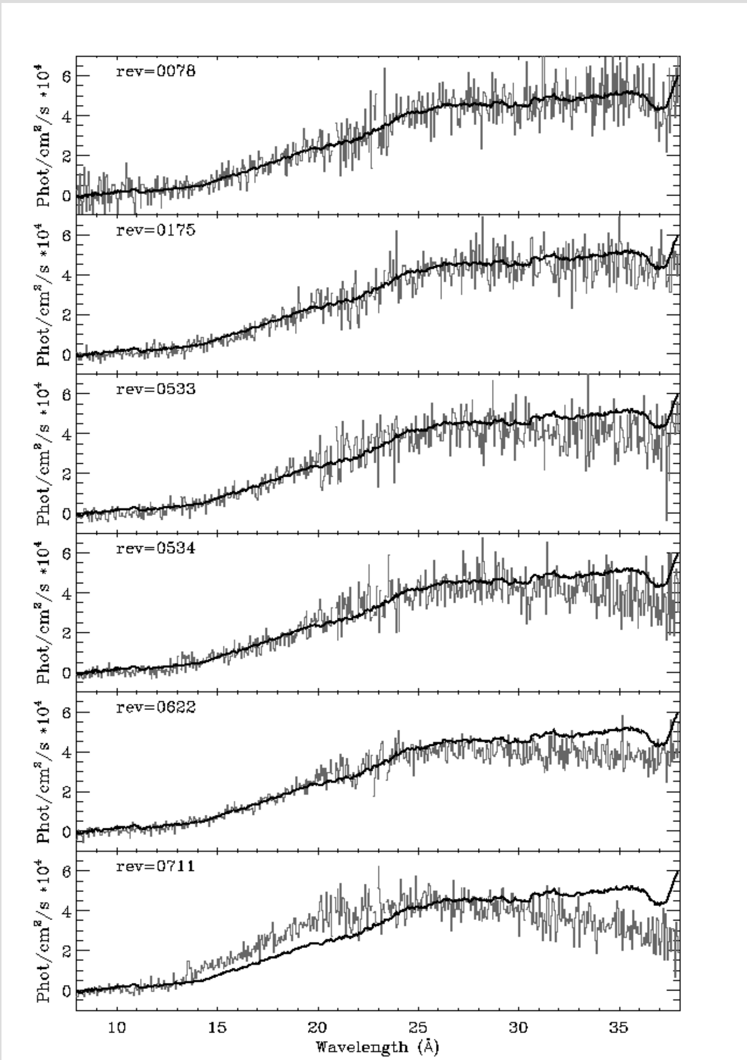
offset $\sim 20^{o}$

Two spots with different parameters and not antipodal!

Long-term spectral changes from RX J0720.4-3125

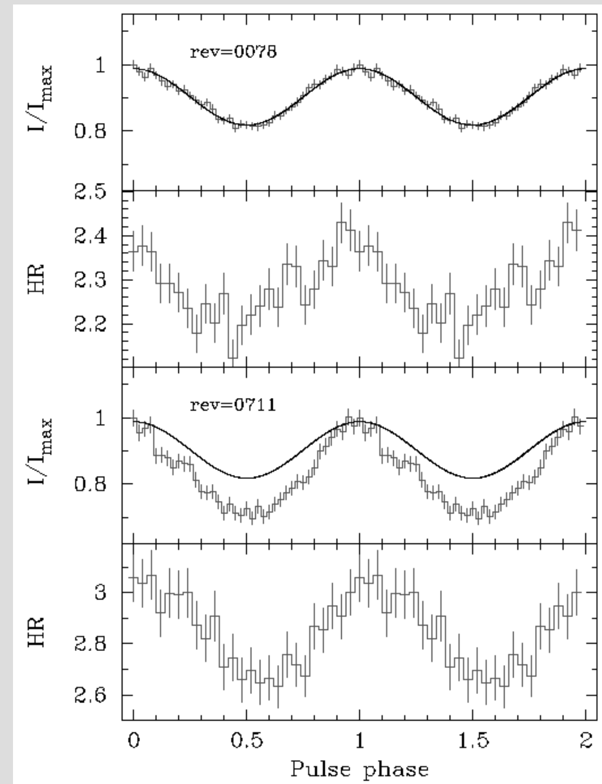
Increase at short wavelength: temperature increase
Decrease at long wavelength: deeper absorption line

XMM-Newton RGS



Increase in pulsed fraction
Phase shift in hardness ratios
varying phase lag between soft and hard emission?

XMM-Newton EPIC-pn

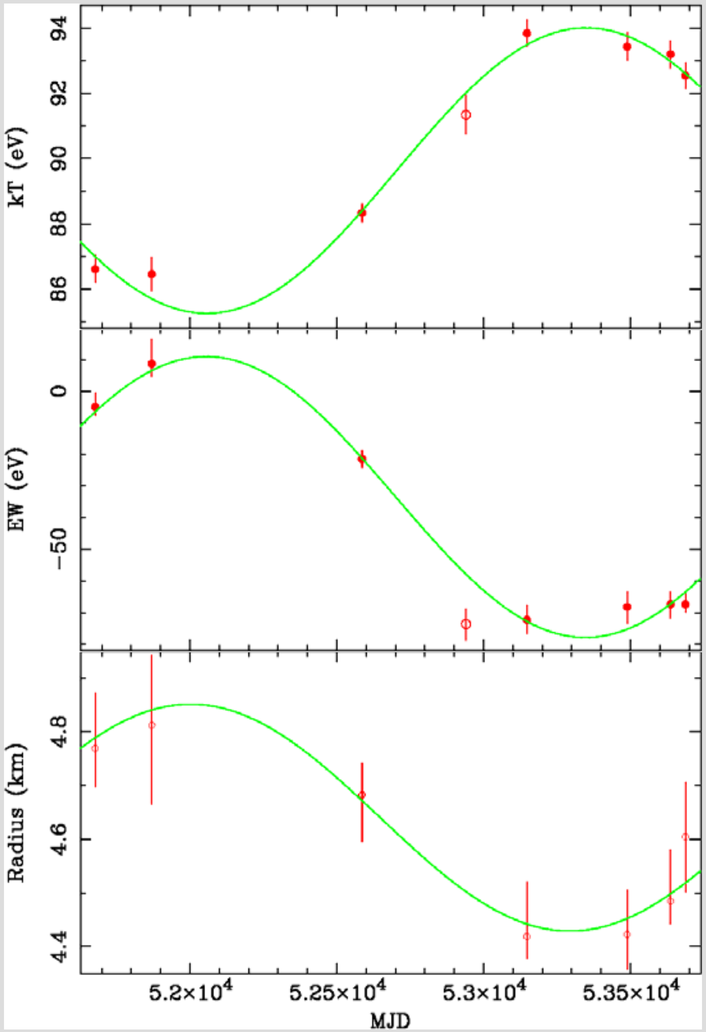


Precession of the neutron star?

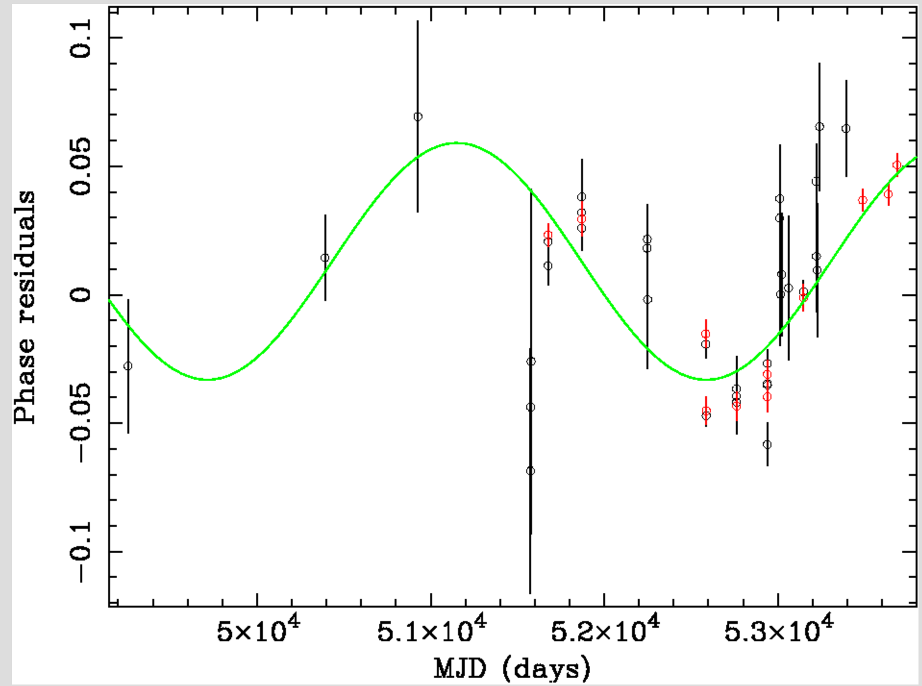
de Vries et al. (2004)

RX J0720.4-3125 longterm spectral variations

Haberl et al. 2006 A&A 451, L17



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

$\varepsilon = (I_3 - I_1) / I_1 = P_{spin} / P_{prec} \approx 4 \cdot 10^{-8}$ (moments of inertia for a rigid body)

between that reported from of radio pulsars and Her X-1

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**

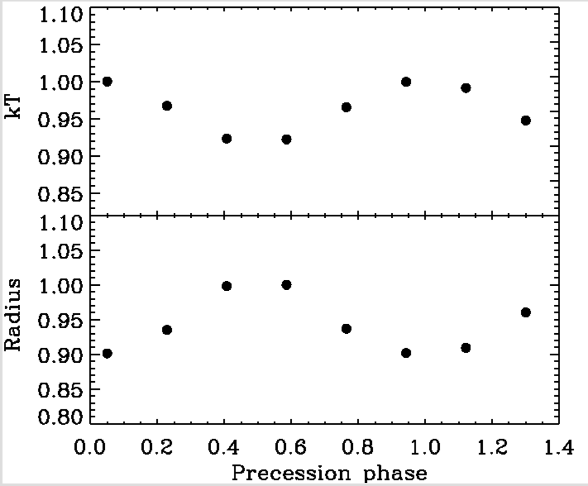
$T_1 = 80$ eV $\sin\theta_1 = 0.8$

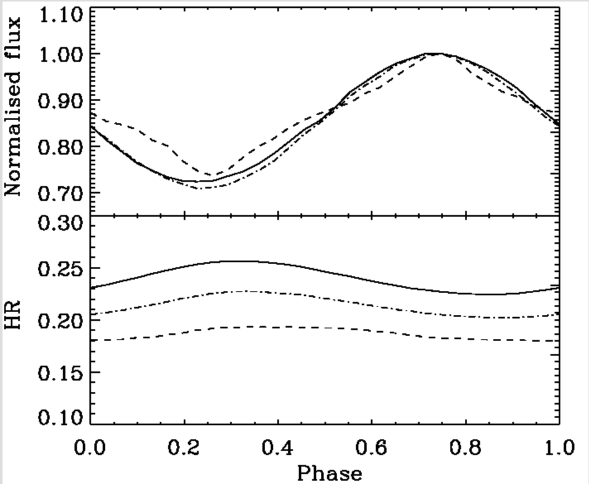
$T_2 = 100$ eV $\sin\theta_2 = 0.6$

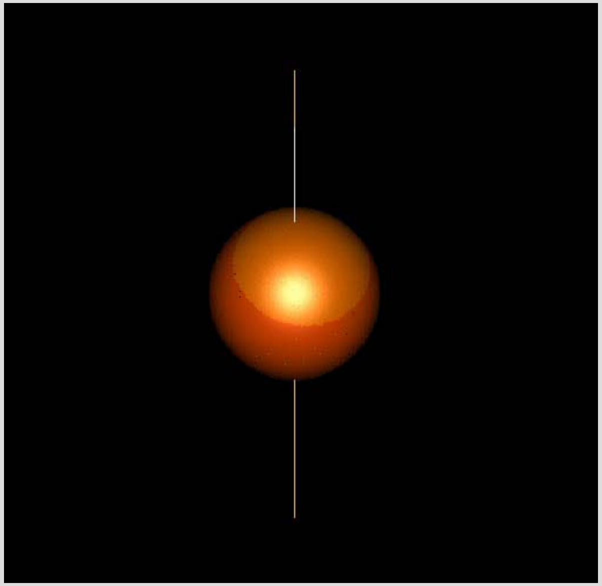
not exactly antipodal:

phase shift of lag between hard and soft emission

$\theta_0 = 160^o$







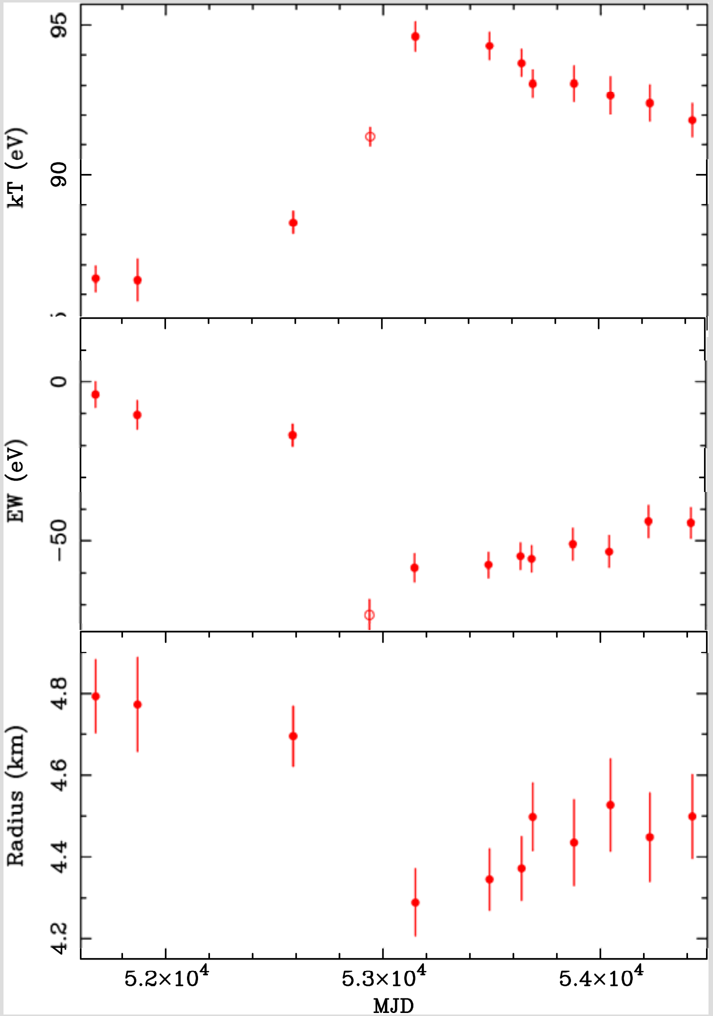
© Roberto Turolla

Haberl et al. (2006), ***A&A 451, L17***

See also: Perez-Azorin et al. (2006), ***A&A 459, 175*** (different emission geometry)

RX J0720.4-3125 longterm spectral variations

Hohle et al. in preparation



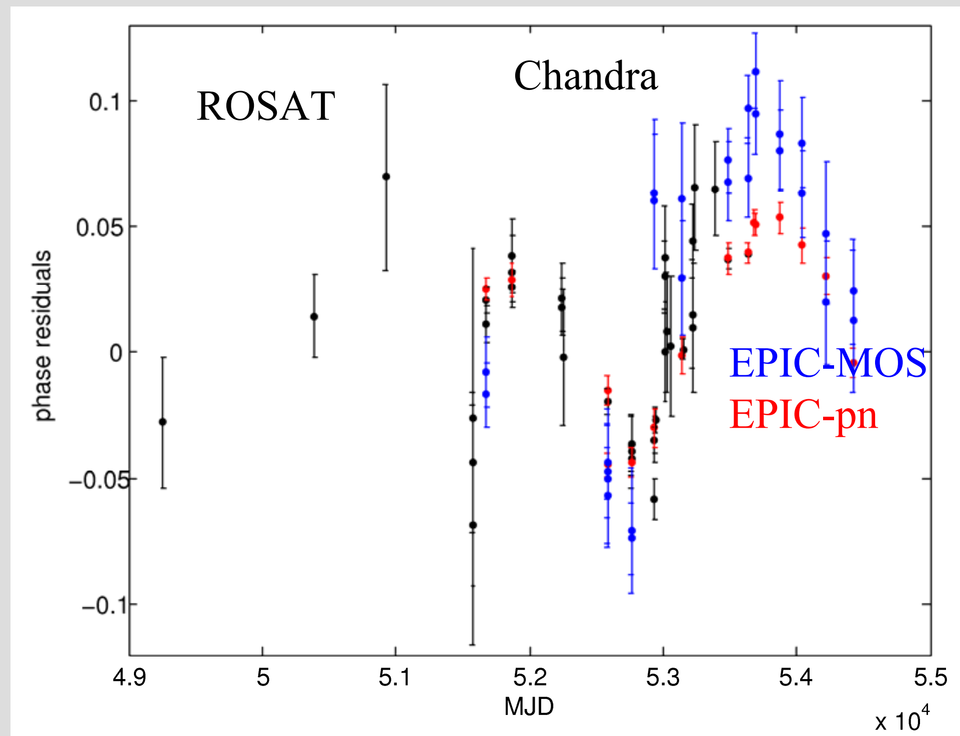
~~Sinusoidal~~ variations in spectral parameters

Period ~~7.1 ± 0.5~~ years **longer**

Phase residuals:

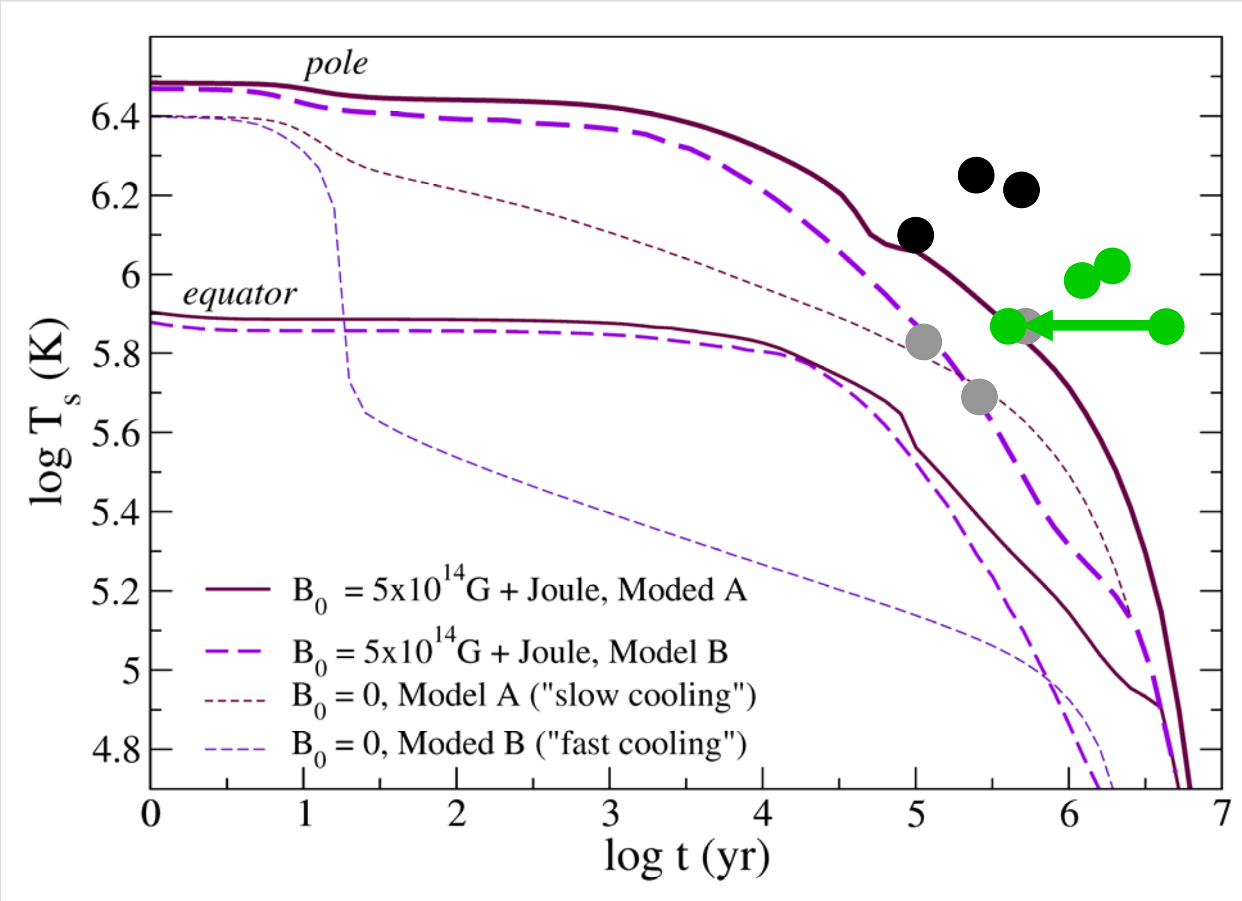
Systematic difference between instruments

energy dependence?



Cooling of magnetized neutron stars

Aguilera et al. 2008 (arXiv:0710.0854v2)



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

Magnetic field decay

Strong effects on

- **the surface temperature distribution**
- **the thermal evolution**

Summary

Isolated cooling neutron stars

The three musketeers

10^{5-6} years (dP/dt)

(1-5)x10^6 G (dP/dt)

The magnificent seven

a few 10^6 years from dP/dt, shorter from kinematic ages

10^{13} G (dP/dt + absorption features)

Influence of the magnetic field on

surface temperature distribution

hot poles - assymetries

thermal evolution

reliable age estimates needed from observations

- **The idealized picture of a neutron star with uniform surface temperature and dipolar magnetic field is too simple.**
- **Evidence for magnetic field decay.**