The Magnificent Seven -

Nearby Cooling Neutron Stars with 10^{13} Gauss Magnetic Fields

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The ROSAT discovery of thermal, radio quiet isolated neutron stars

New XMM-Newton and Chandra observations

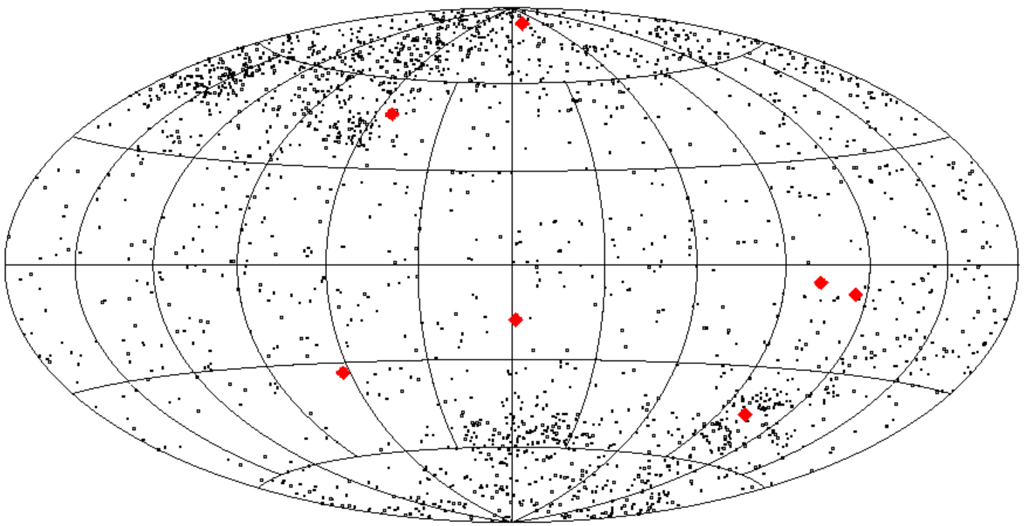
- **Magnetic field estimates**
  - **Absorption features in the X-ray spectra**
  - **Pulse timing**
- **The case of RX J0720.4-3125**
  - **Spectral variations on long-term time scales**
  - **Evidence for free precession**

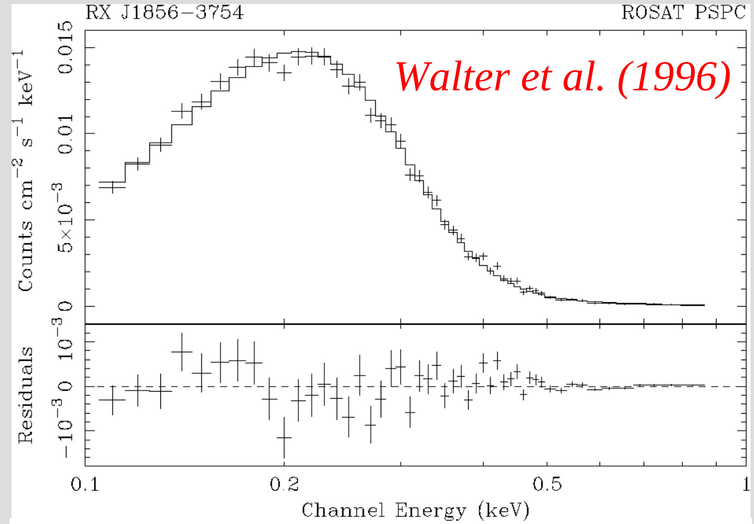
Fenomec Mini Workshop on Magnetic Fields and Neutron Stars Surface

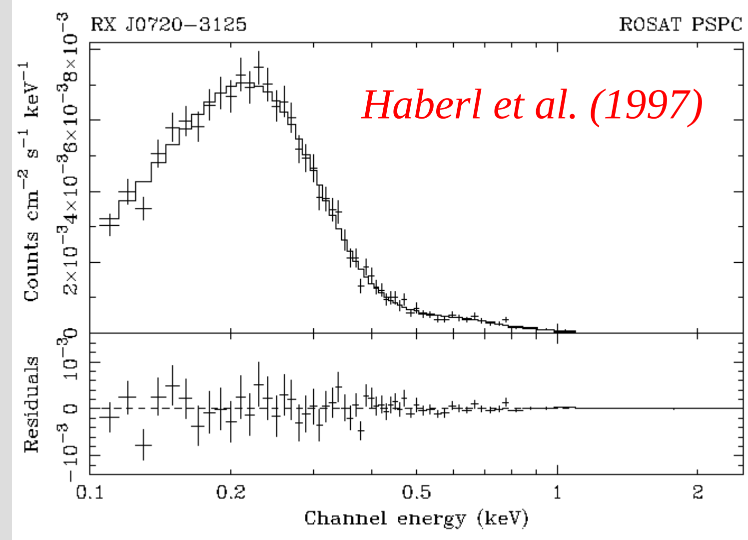
Cocoyoc, Mexico, February 12 - 14, 2007

The Magnificent Seven: Thermal, radio-quiet neutron stars

Soft X-ray spectrum + faint in optical



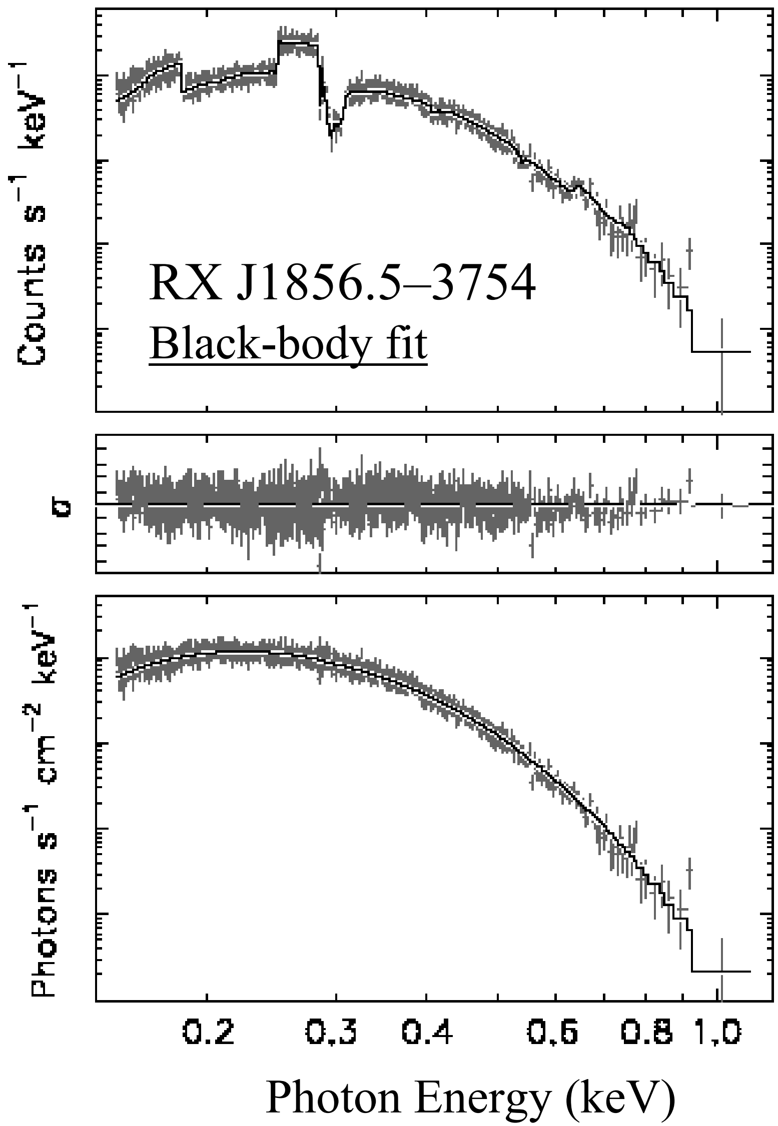




PSPC cts/s	HR1	HR2	Name
0.15 ± 0.01	-0.96 ± 0.03	-0.45 ± 0.73	RX J0420.0-5022
0.23 ± 0.03	-0.06 ± 0.12	-0.60 ± 0.17	RBS1774 = 1RXS J214303.7+065419
0.29 ± 0.02	-0.20 ± 0.08	-0.51 ± 0.11	RBS1223 = 1RXS J130848.6+212708
0.38 ± 0.03	-0.74 ± 0.02	-0.66 ± 0.08	RX J0806.4-4123
0.78 ± 0.02	-0.67 ± 0.02	-0.68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

The X-ray spectrum of RX J1856.5–3754

Chandra LETGS



$n_H = (9.5 \pm 0.03) \cdot 10^{19}$ cm

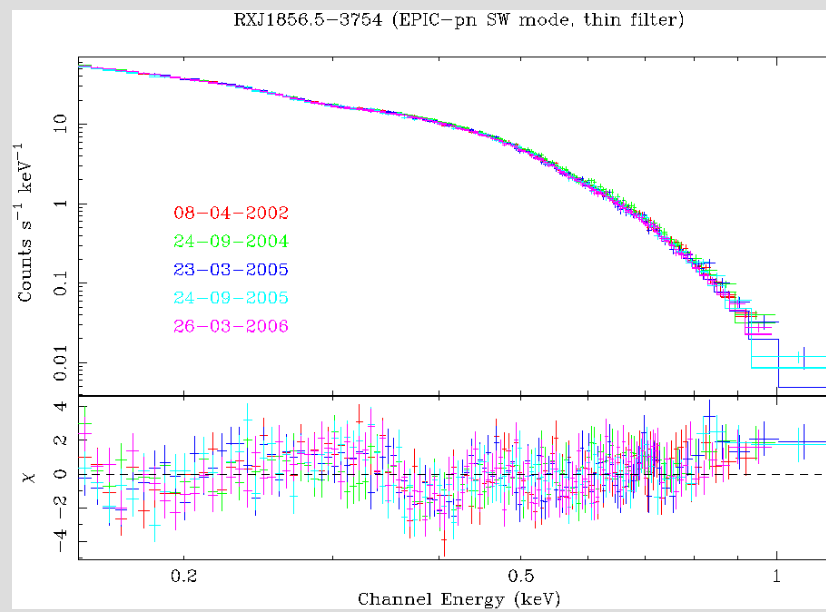
$kT_\infty = 63.5 \pm 0.2$ eV

$R_\infty = 4.4 \pm 0.1$ km (120pc)

$L_{bol} = 4.1 \cdot 10^{31}$ erg s^{-1}

No narrow absorption features !

Burwitz et al. (2003)



XMM EPIC-pn

Spectrum constant over time scales of years

Haberl (2006)

Thermal, radio-quiet isolated neutron stars

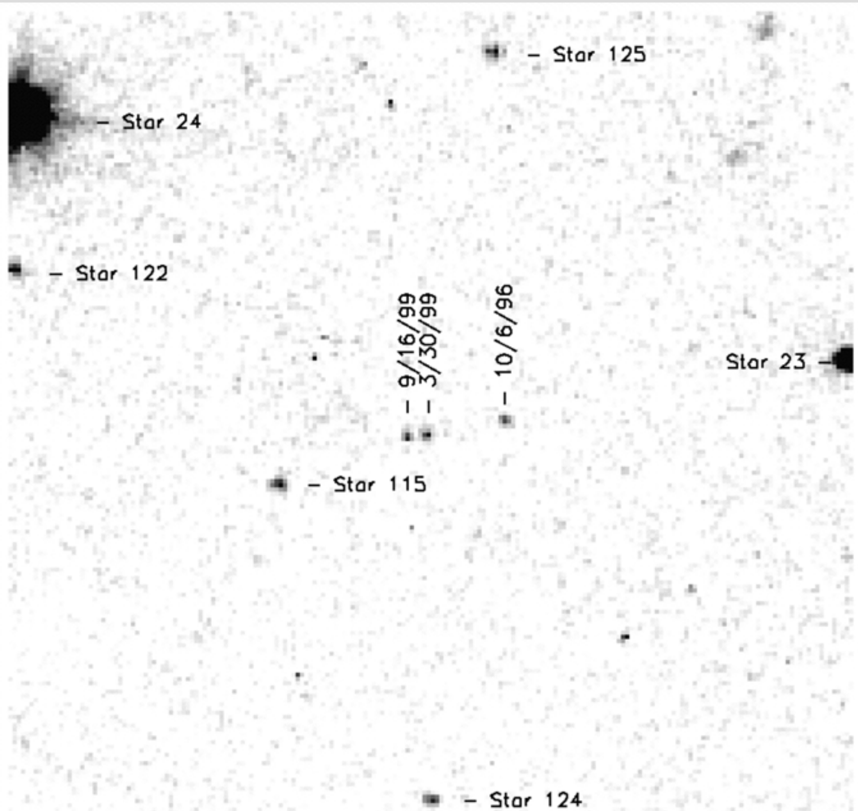
- Soft X-ray sources in ROSAT survey + optically faint → isolated neutron stars
- Blackbody-like X-ray spectra, NO non-thermal hard emission
- Low absorption ~10^{20} H cm^{-2} → nearby (2 cases with measured parallax)
- Luminosity ~10^{31} erg s^{-1}
- Constant X-ray flux on time scales of years
- No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

Best candidates for „genuine“ cooling INSs with undisturbed emission from stellar surface

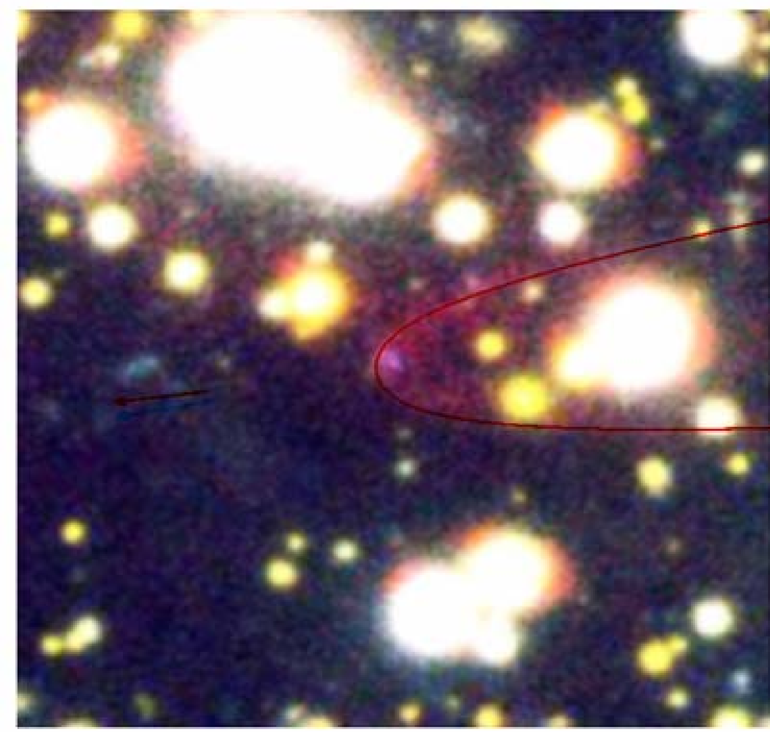
Object	$T/10^6$ K	kT/eV	P/s	Optical	PM/mas/y	distance/pc
RX J0420.0–5022	0.51	44	3.45	B = 26.6		
RX J0720.4–3125	0.99-1.10	85-95	8.39	B = 26.6	97	330 +170/-80
RX J0806.4–4123	1.11	96	11.37	B > 24		
RX J1308.8+2127*	1.00	86	10.31	m_{50ccd} = 28.6		
RX J1605.3+3249	1.11	96	6.88?	B = 27.2	145	
RX J1856.5–3754	0.73	62	7.06	B = 25.2	332	161 +18/-14
RX J2143.0+0654**	1.17	102	9.44	B > 26		

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

RX J1856.5-3754: optical



Distance 161 +18/–14 pc HST



Bowshock Nebula VLT

High proper motion:
Not heated by accretion of ISM !!
Cooling isolated neutron star

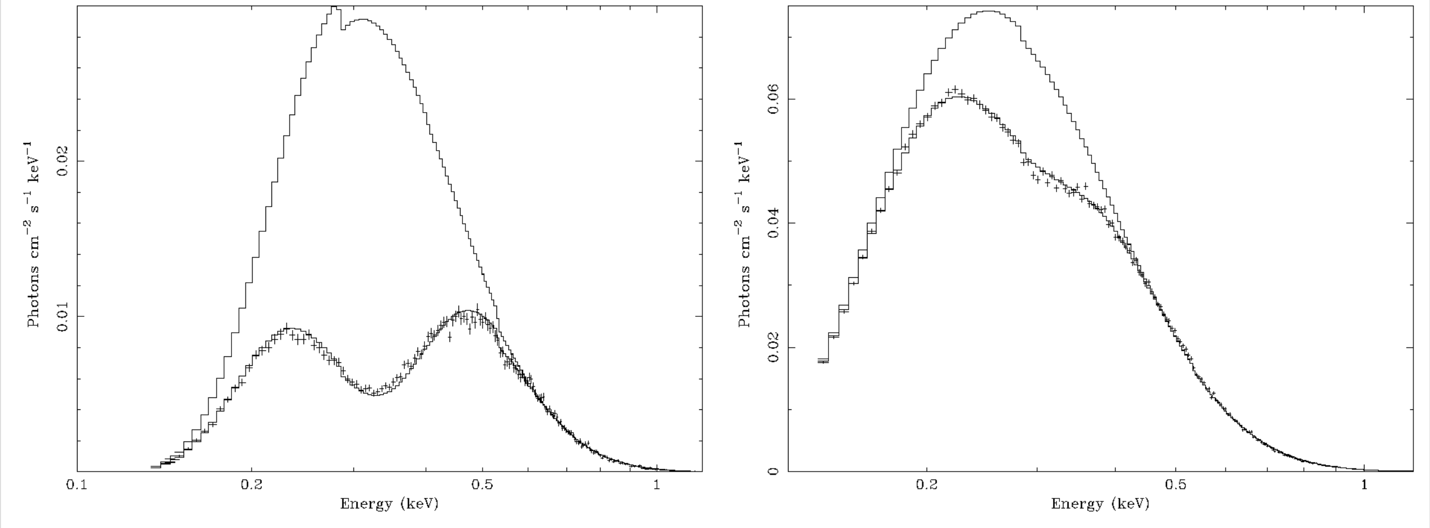
van Kerkwijk & Kaplan (2006)

Powered by magnetic dipole braking:
$dE/dt = 4.5\text{x}10^{32}$ erg s^{-1}, $t = 5\text{x}10^{5}$ y
$B \approx 10^{13}$ G

Braje & Romani (2002)
Trümper et al. (2004)

XMM-Newton observations of the M7: absorption features

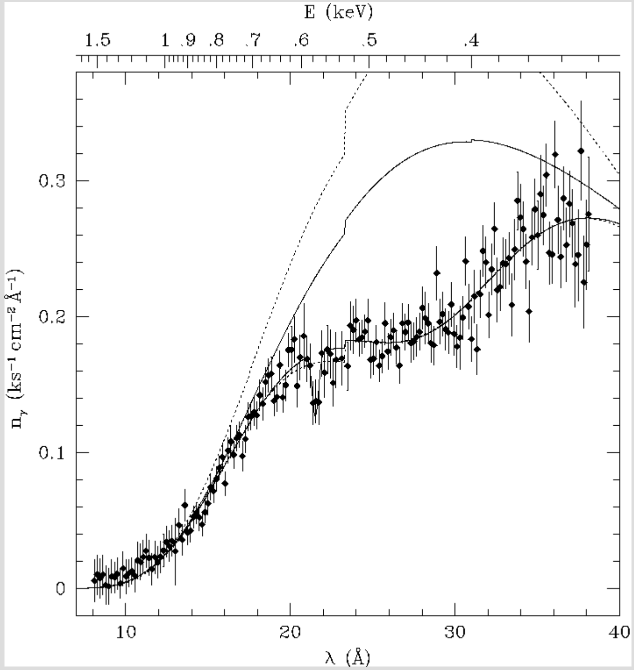
RBS 1223
EW = 150 eV
Pulse phase variations



XMM-Newton EPIC-pn

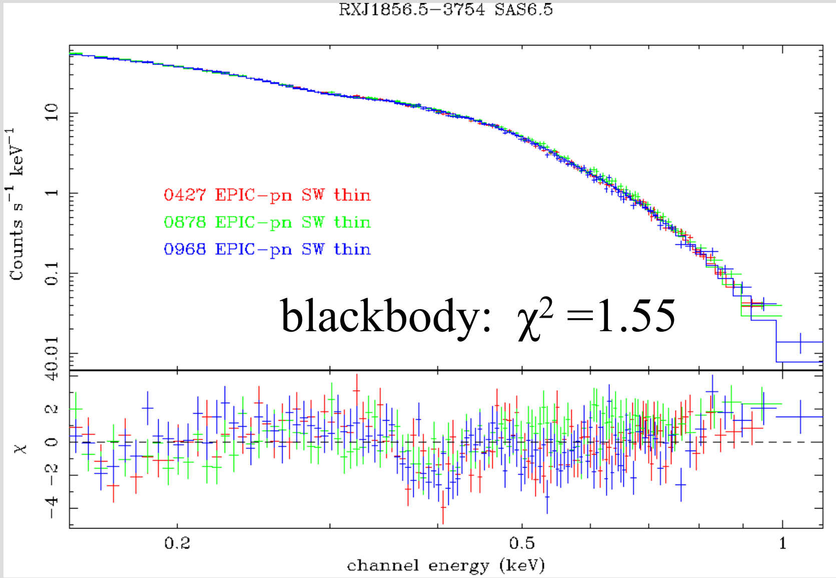
RX J0720.4-3125
EW = 40 eV variable with pulse phase and over years

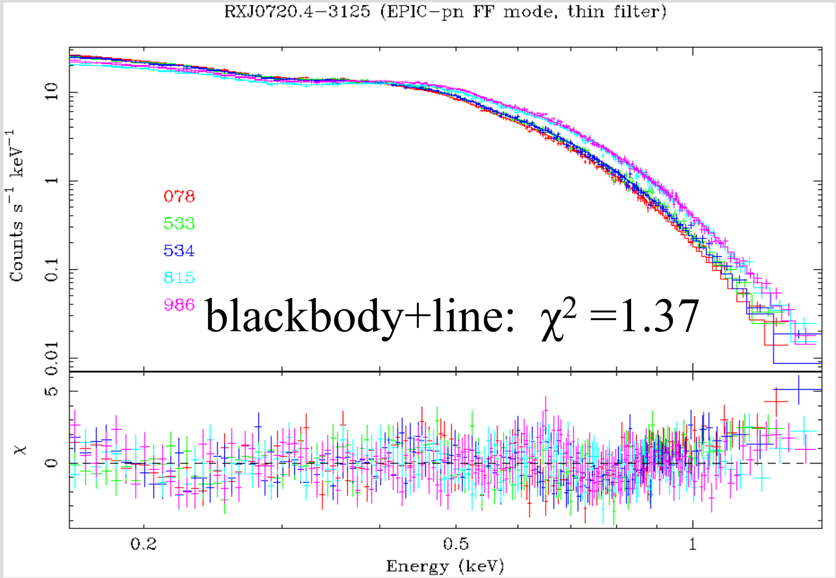
XMM-Newton RGS

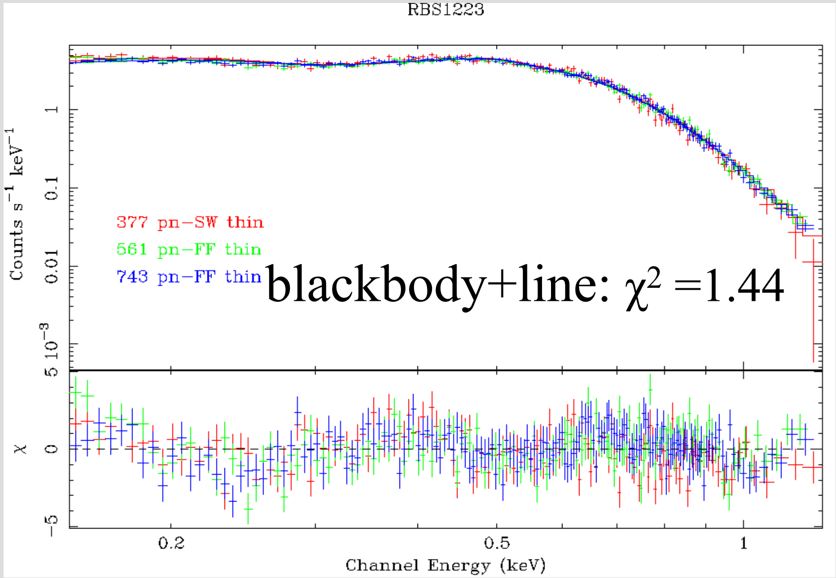


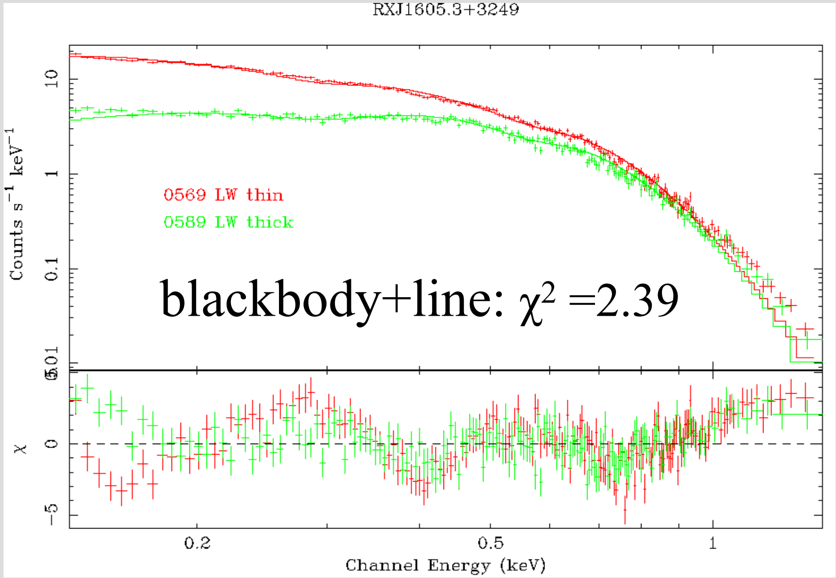
RX J1605.3+3249
kT = 95 eV
N_H = 0.8 · 10^{20} cm^{-2}
E_{line} = 450 – 480 eV
Van Kerkwijk et al. (2004)

Evidence for multiple lines:

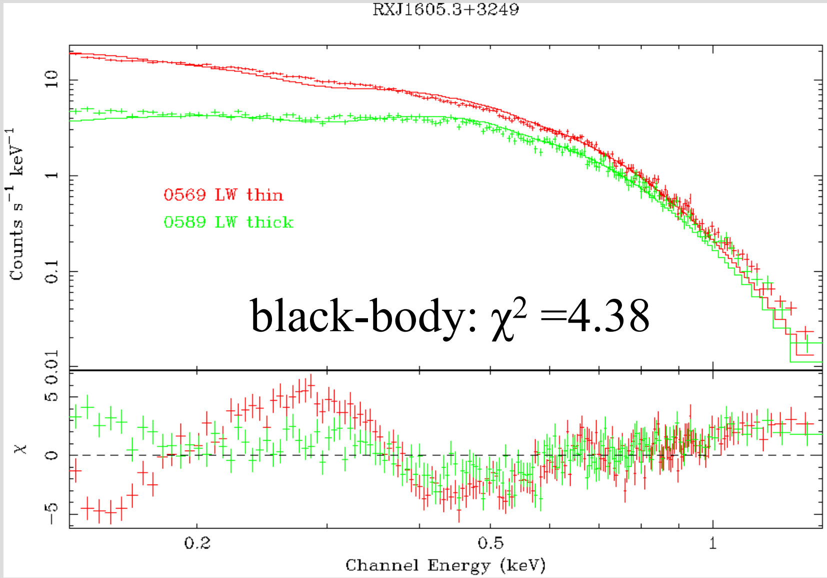


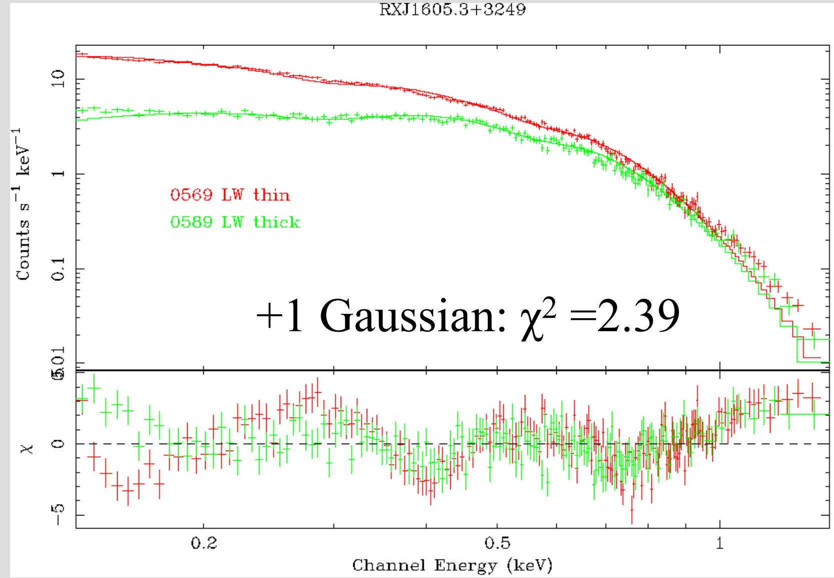


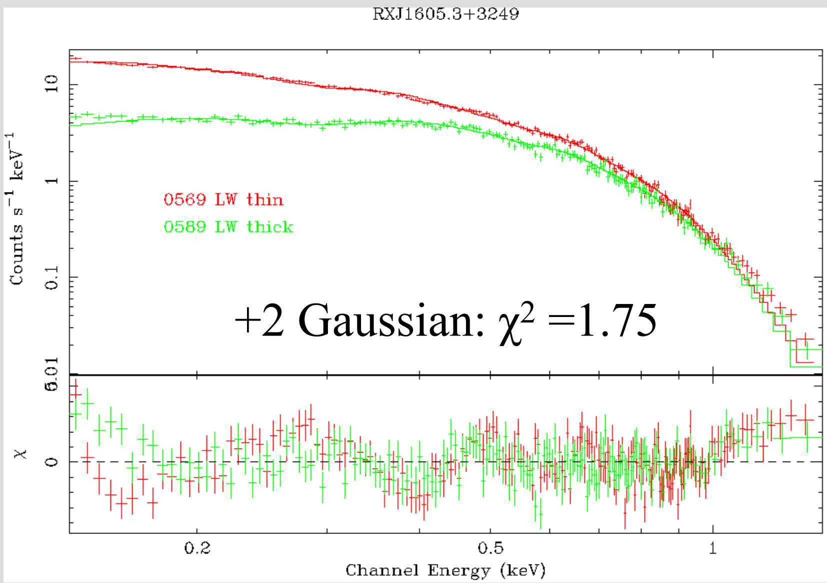


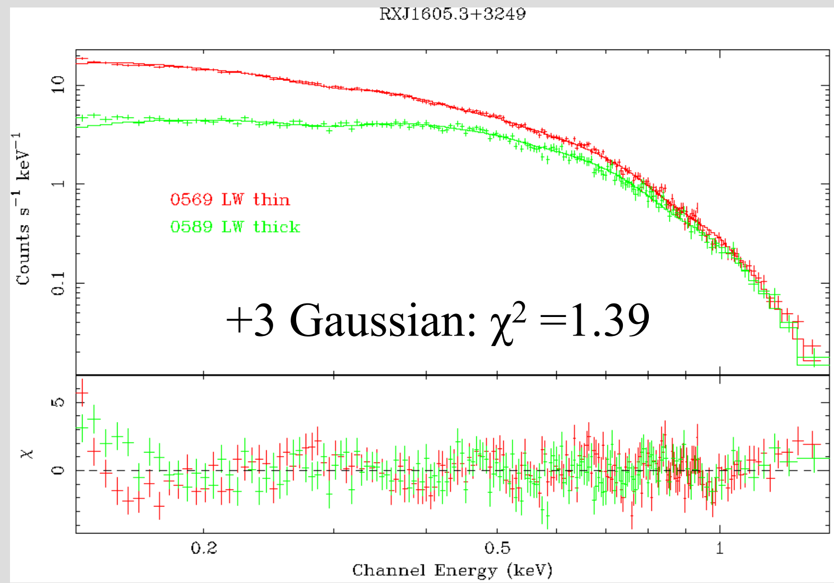


RX J1605.3+3249: Evidence for three lines









RX J1605.3+3249: Three absorption lines with regular energy spacing

Line energies:

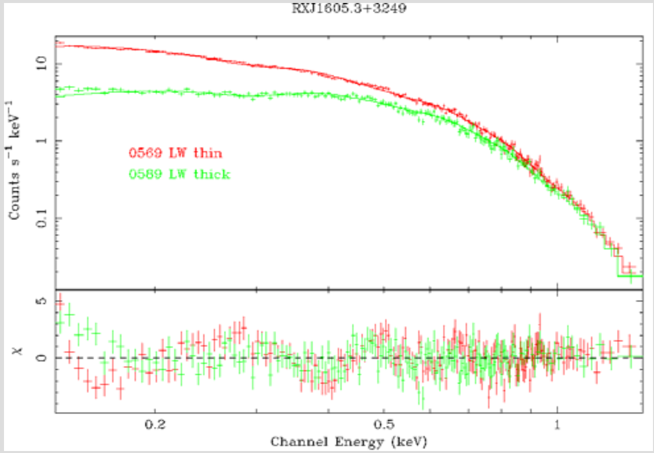
$E_1 = 403 \pm 2$ eV
$E_2 = 589 \pm 4$ eV
$E_3 = 780 \pm 24$ eV
$E_2/E_1 = 1.46 \pm 0.02$
$E_3/E_1 = 1.94 \pm 0.06$
$E_3/E_2 = 1.32 \pm 0.04$

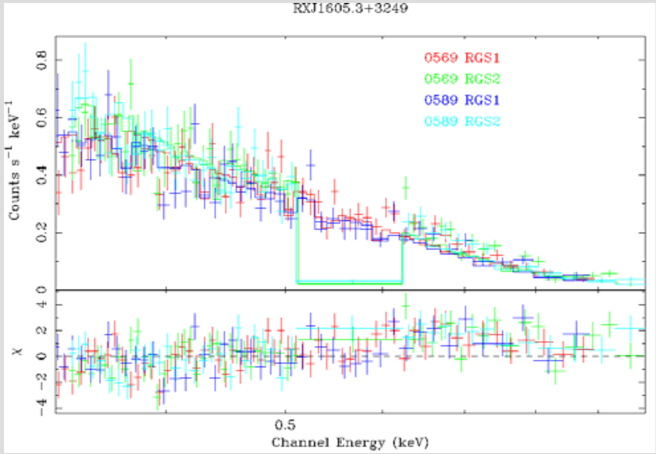
$E_1 : E_2 : E_3 = 1 : 1.5 : 2$

Absorbed line fluxes:

$N_1 = -(4.3 \pm 0.1) \cdot 10^{-3}$ ph/cm²/s $\quad EQW_1 = 96$ eV
$N_2 = -(8.0 \pm 0.8) \cdot 10^{-4}$ ph/cm²/s $\quad EQW_2 = 76$ eV
$N_3 = -(1.6 \pm 0.4) \cdot 10^{-5}$ ph/cm²/s $\quad EQW_3 = 67$ eV
$N_1/N_2 = 5.38 \pm 0.54$
$N_2/N_3 = 5.00 \pm 1.35$

$N_1 : N_2 : N_3 \sim 25 : 5 : 1$
(common line $\sigma = 87$ eV)





RBS1223: Evidence for lines at 230 eV and at 460 eV (Schwope et al. 2006, London)
RX J0806.4-4123: also two lines?

The origin of the absorption features

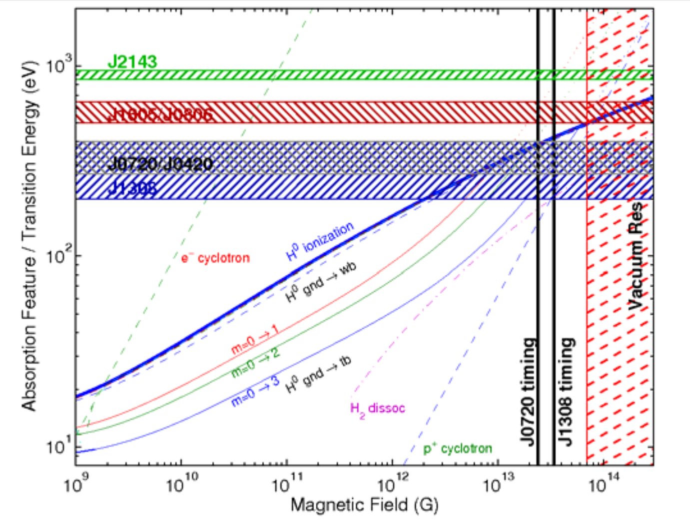
Proton cyclotron absorption line ?

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

Atomic line transitions ?

Hydrogen ?

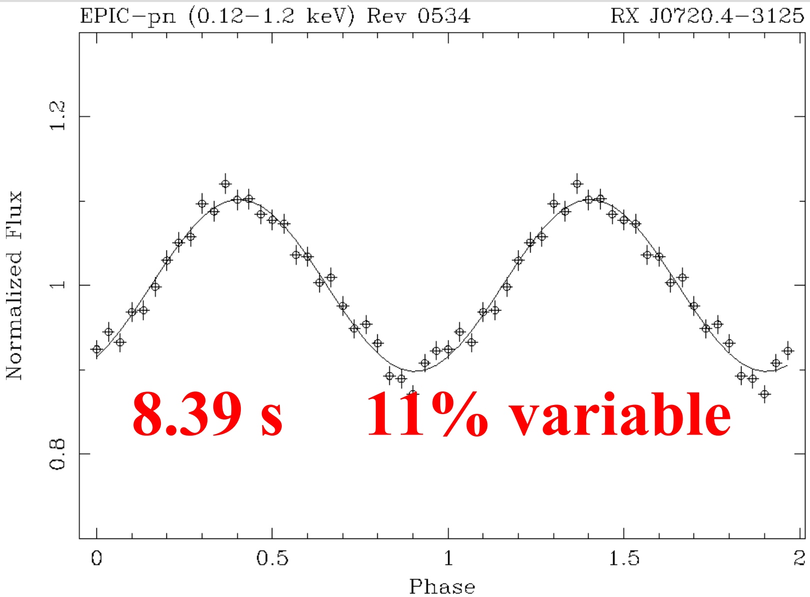
Mixture ?

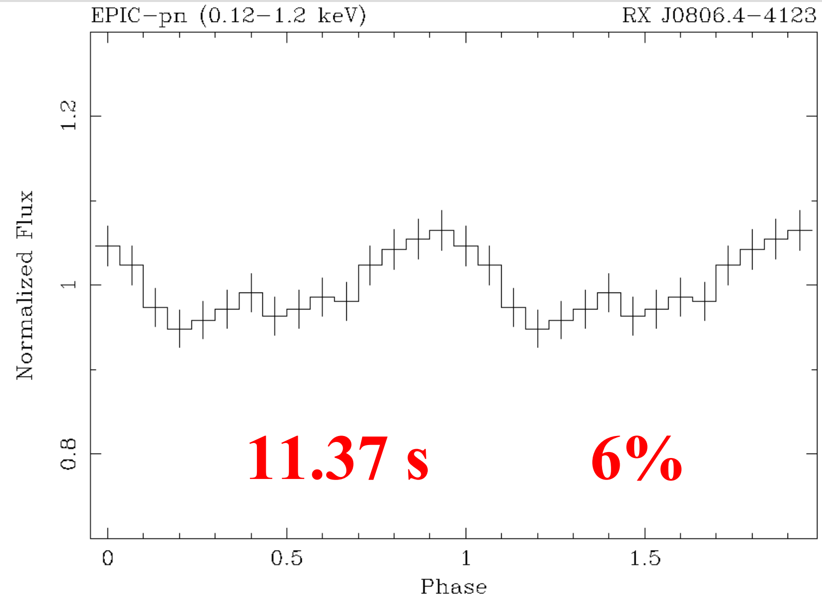


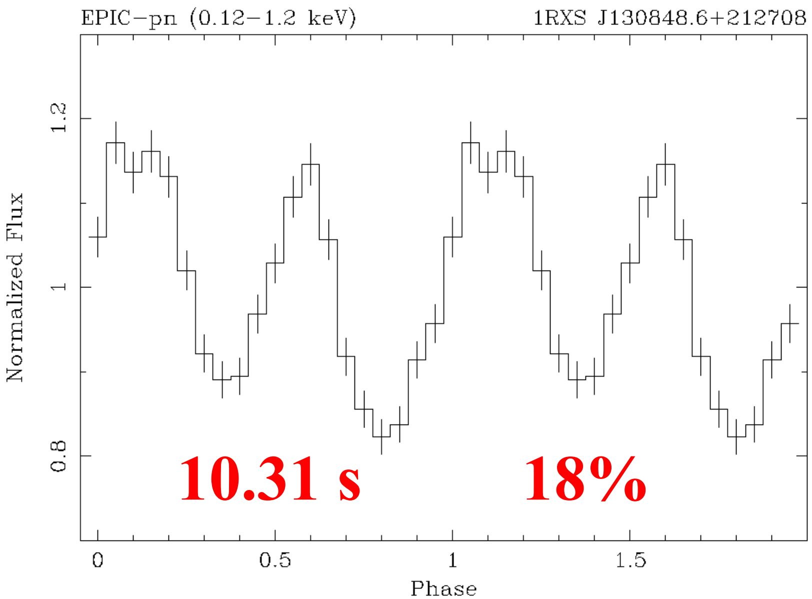
van Kerkwijk & Kaplan 2006, astro-ph/0607320

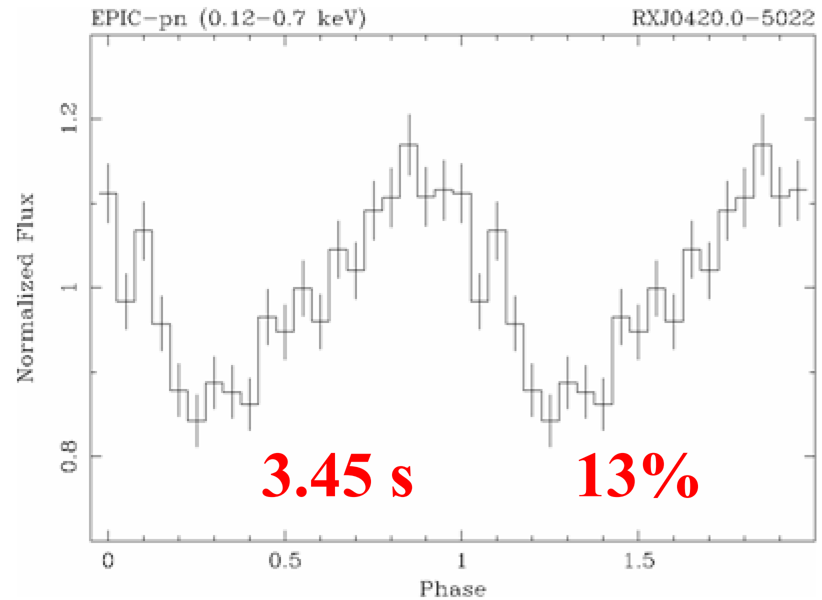
In any case B ≈ $10^{13} - 10^{14}$ G

X-ray pulsations

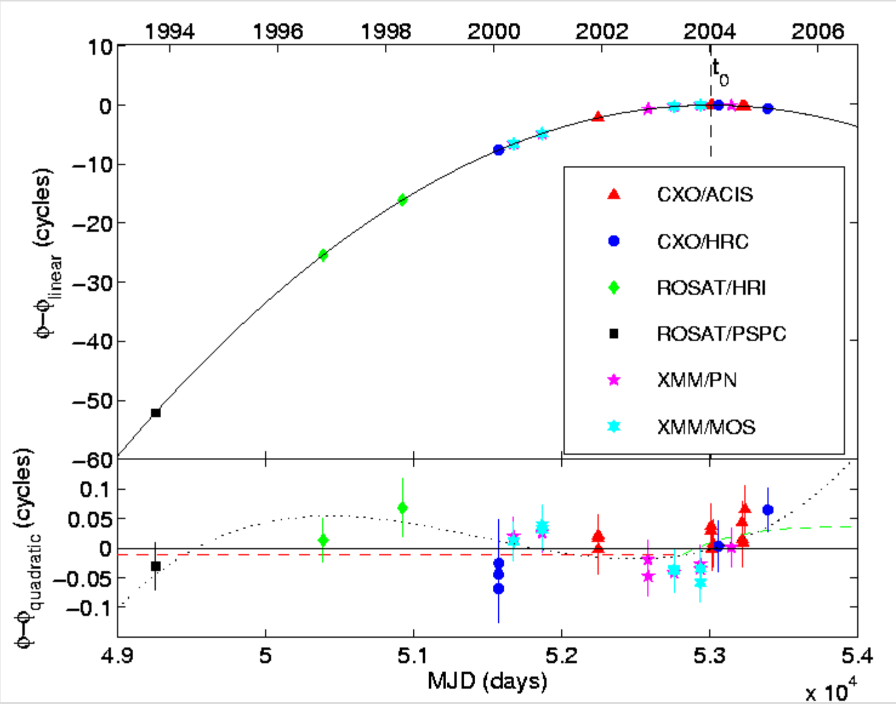


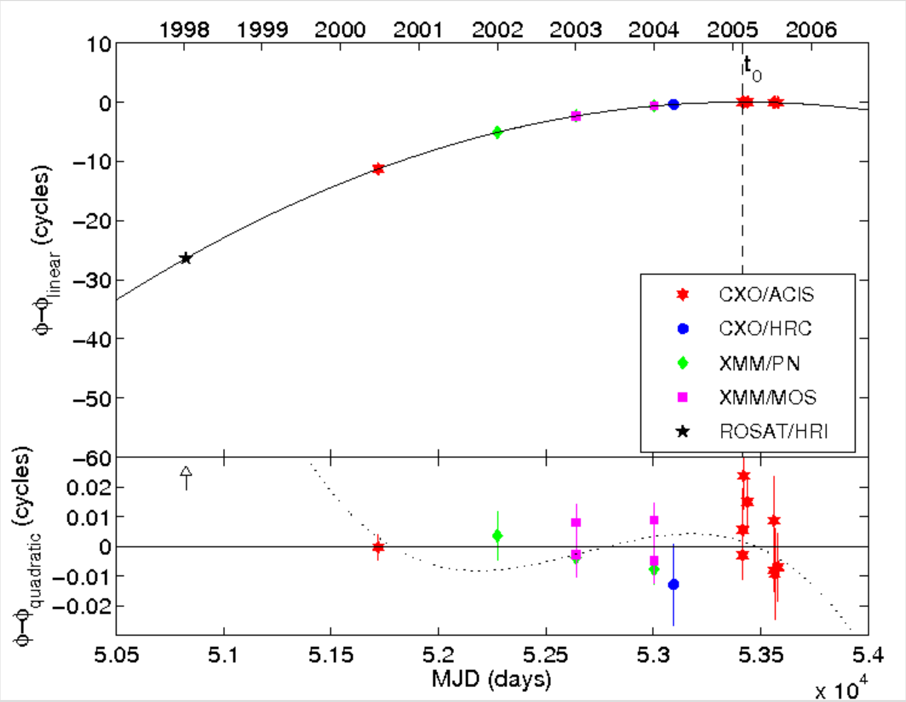






Period history: RX J0720.4–3125 and RBS 1223





P = 8.39 s

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

τ = 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}

τ = P/2(dP/dt) = $1.5 \cdot 10^6$ y

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

Kaplan & van Kerkwijk 2005
ApJ 635, L65

Magnetic fields

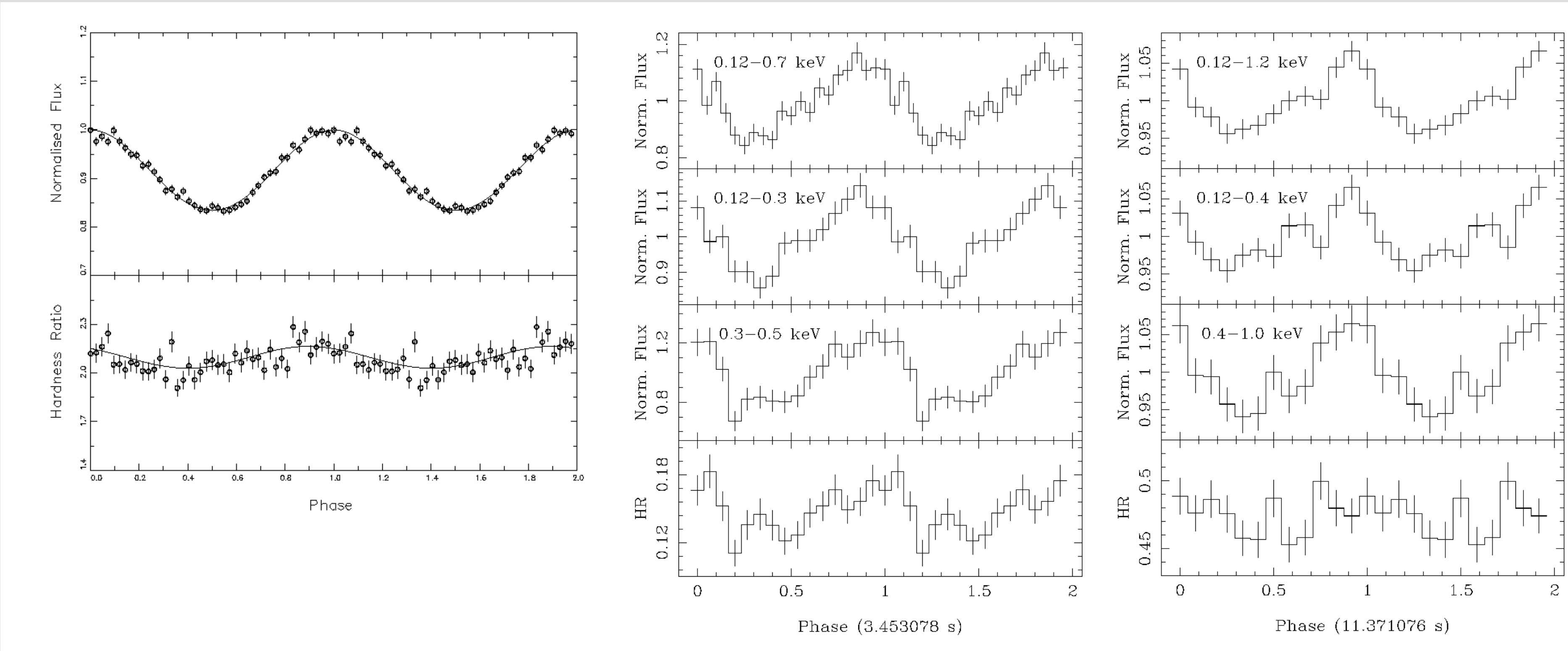
Unique opportunity to estimate B in two independent ways:

- 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_{abs} [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%	< 19	–	4.2[c)]	–
1RXS J2143.0+0654	9.43	4%	<60[d)]	750	< 24[d)]	15

a) Spectral fit with single line / two lines
b) With single line / three lines at 400 eV, 600 eV and 800 eV
c) Based on age of 5×10^5 years
Estimate from Hα nebula assuming that it is powered by magnetic dipole breaking: $\sim 1 \times 10^{13}$ G
d) Radio detection: Malofeev et al. 2006, ATEL 798

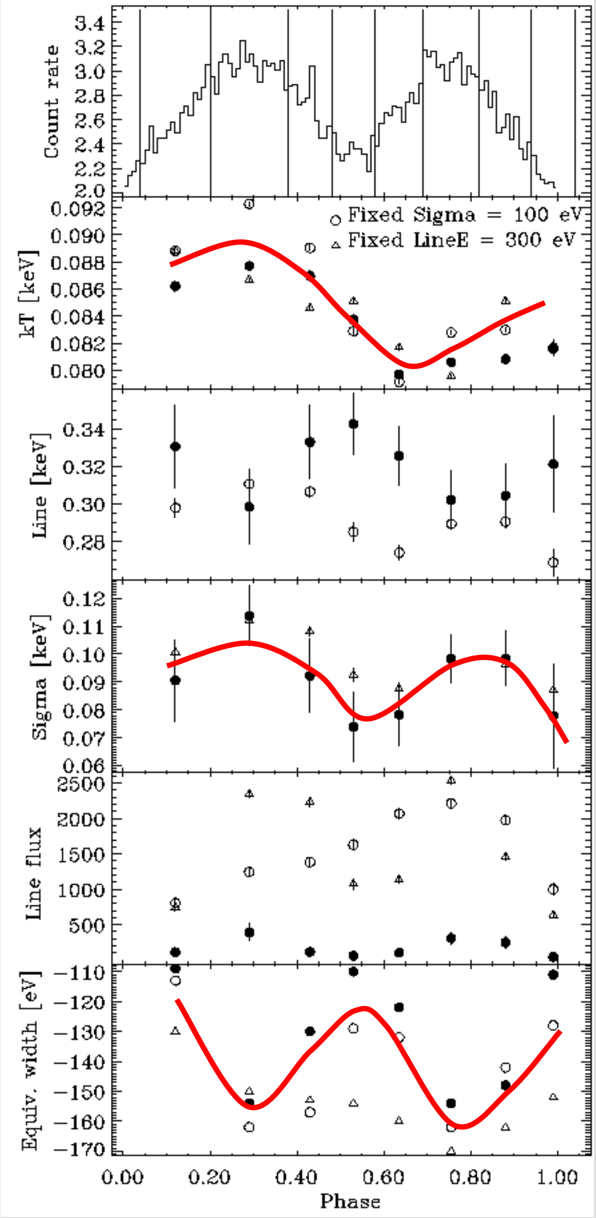
Spectral variations with pulse phase

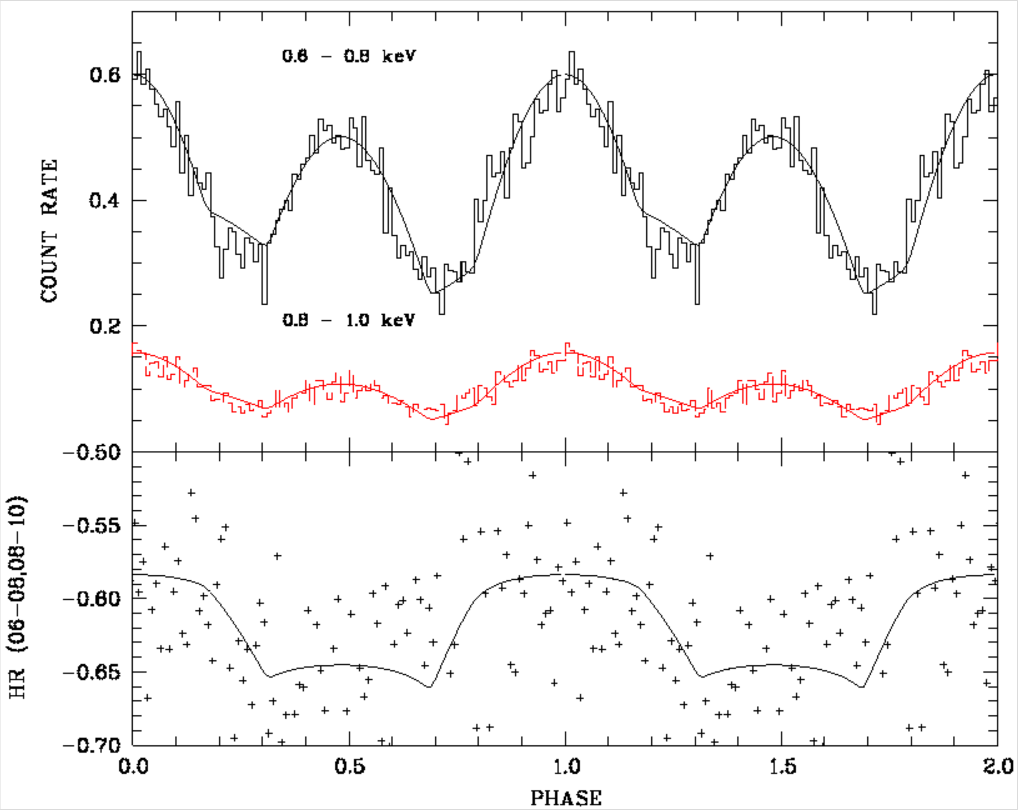


RX J0720.4-3125 **RX J0420.0-5022** **RX J0806.4-4123**

Cropper et al. (2001) *Haberl et al. (2005)*

Spectral variations with pulse phase: RBS 1223





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

Two-spot model: kT_{∞} **= 92 eV and 84 eV**

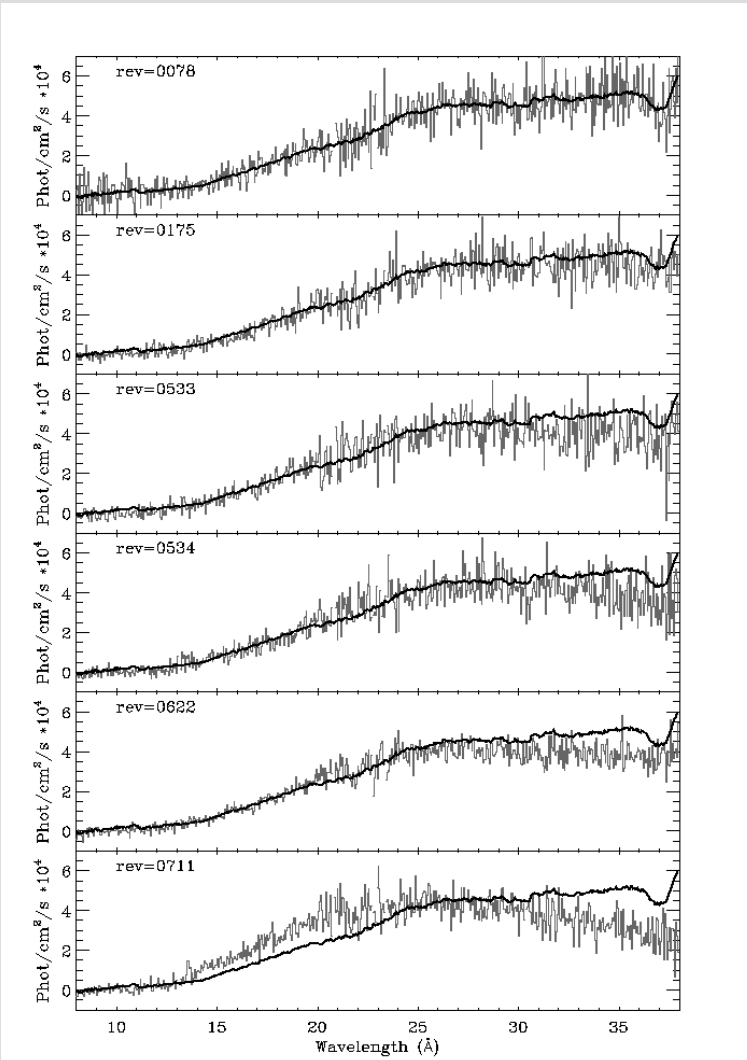
$2\Phi \sim 8^{o}$ **and** $\sim 10^{o}$

offset $\sim 20^{o}$

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

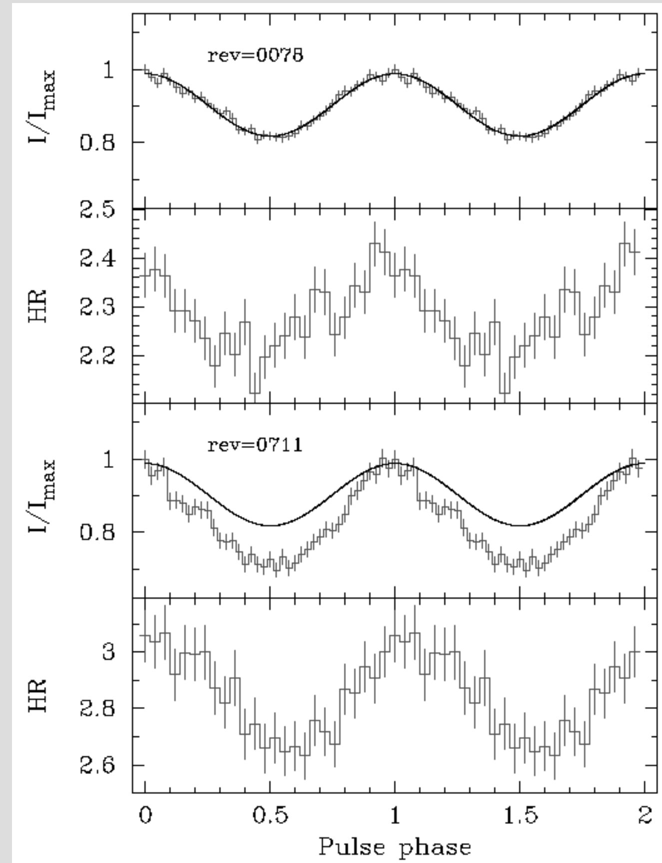
Increase at short wavelength: temperature increase
Decrease at long wavelength: deeper absorption line

XMM-Newton RGS



Increase in pulsed fraction

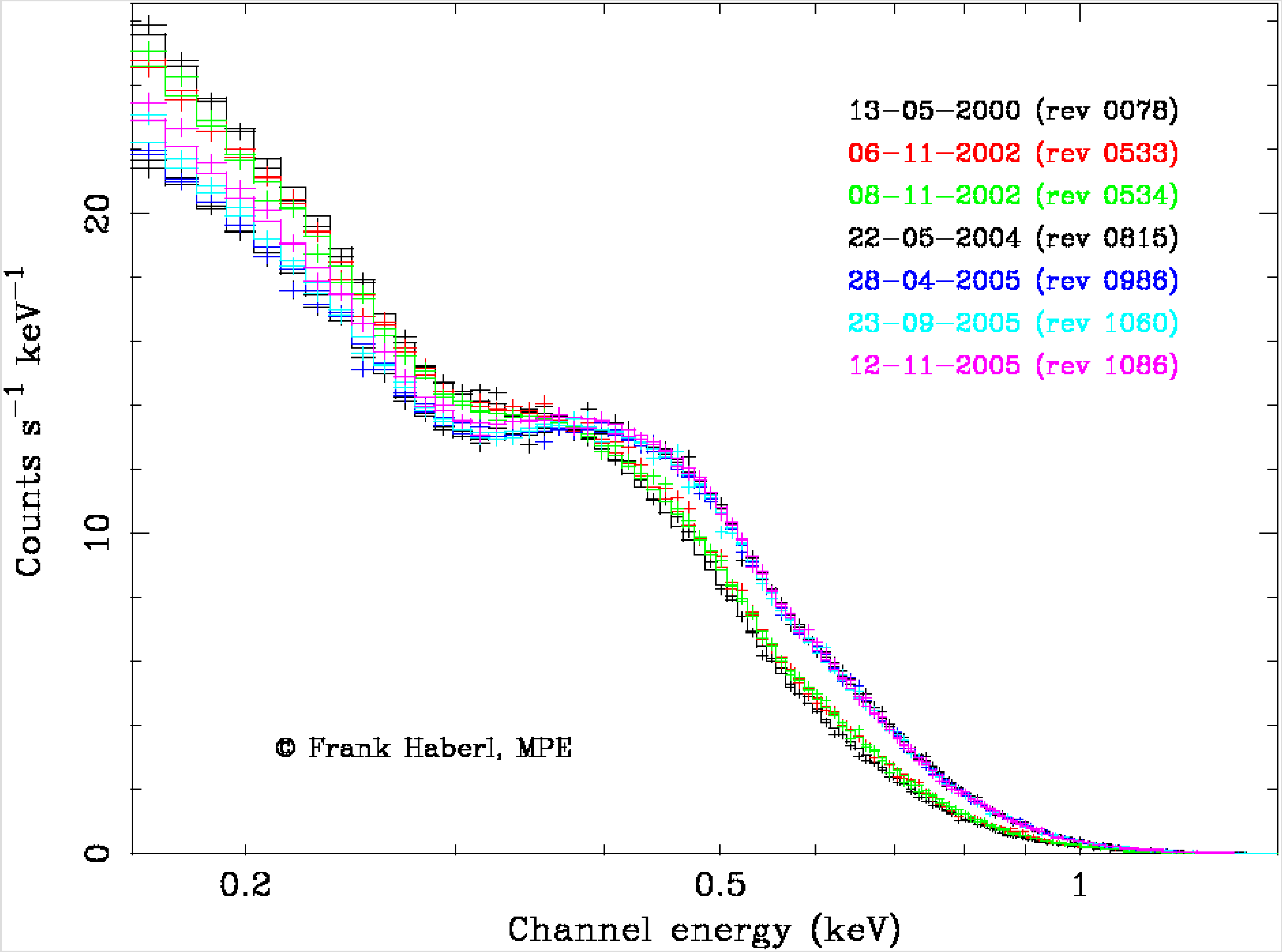
XMM-Newton EPIC-pn



Precession of the neutron star?

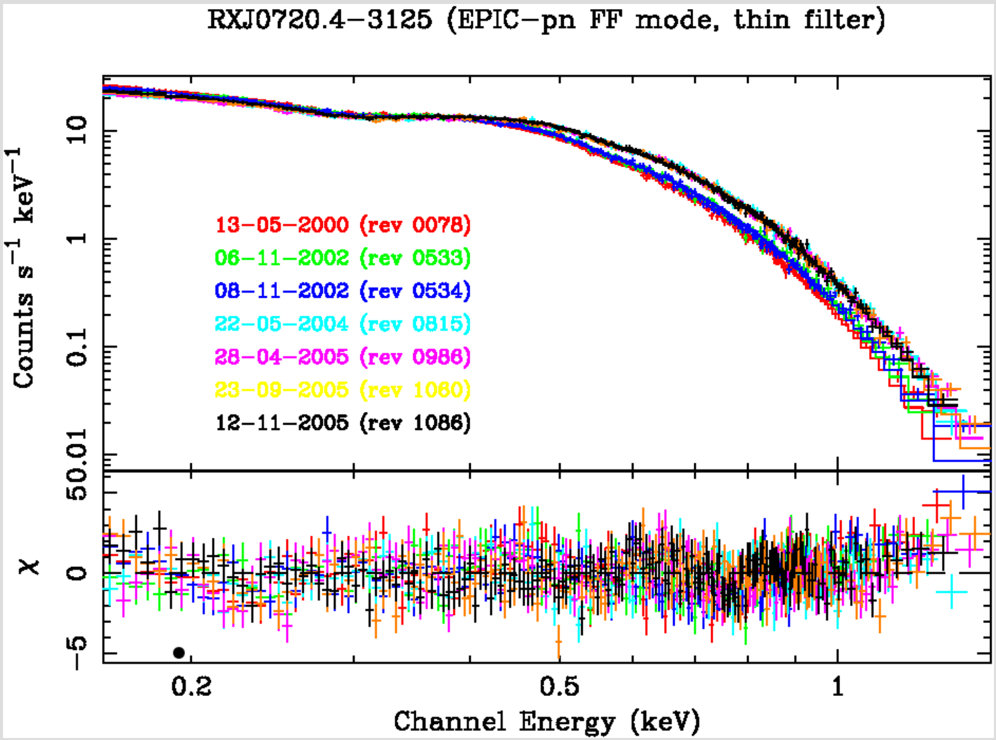
de Vries et al. (2004)

RX J0720.4-3125 longterm spectral variations



RX J0720.4-3125: Spectral variations over 4.5 years

XMM-Newton EPIC-pn



Rev.	kT(eV)	EW(eV)
•0078	86.6 ± 0.4	–5.02 ± 4.5
0175	86.5 ± 0.5	+8.68 ± 7.7
•0533/534	88.3 ± 0.3	–21.5 ± 2.6
0711/711	91.3 ± 0.6	–73.7 ± 4.9
•0815	93.8 ± 0.4	–72.4 ± 4.7
•0986	93.5 ± 0.4	–68.3 ± 5.2
•1060	93.2 ± 0.4	–67.4 ± 4.3
•1086	92.6 ± 0.4	–67.5 ± 3.5

• FF mode + thin filter

common line energy: 280 ± 6 eV
common line width: σ = 90 ± 5 eV

Long-term variations over 5.5 years:

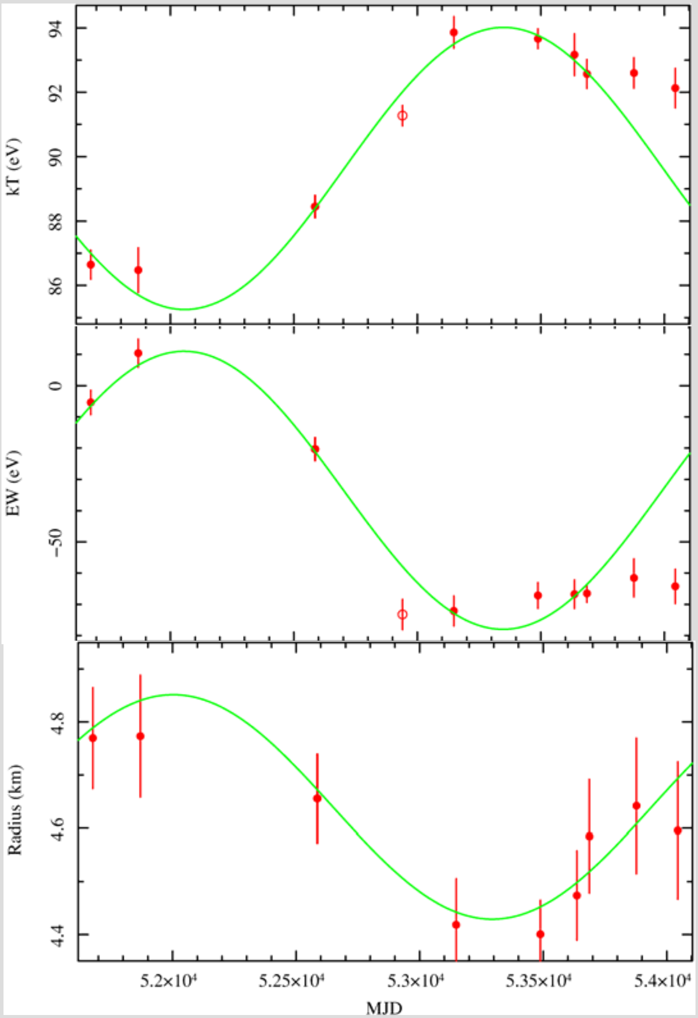
Temperature by ~7 eV

Absorption line equivalent width by ~70 eV

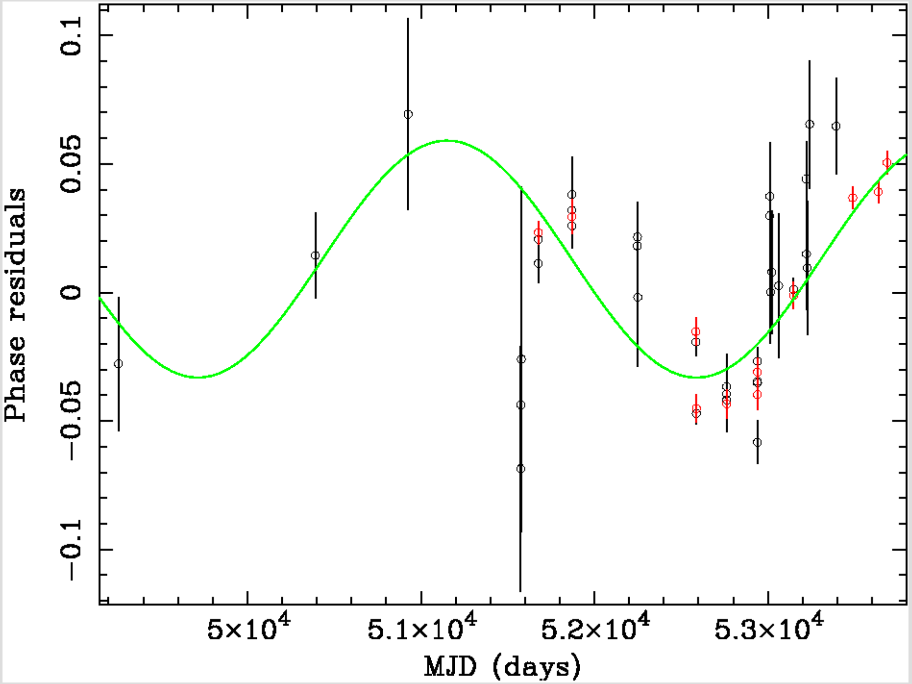
Radius of emission area from 4.4 km to 4.8 km (d=300pc)

But flux is constant within ±2%

RX J0720.4-3125 longterm spectral variations



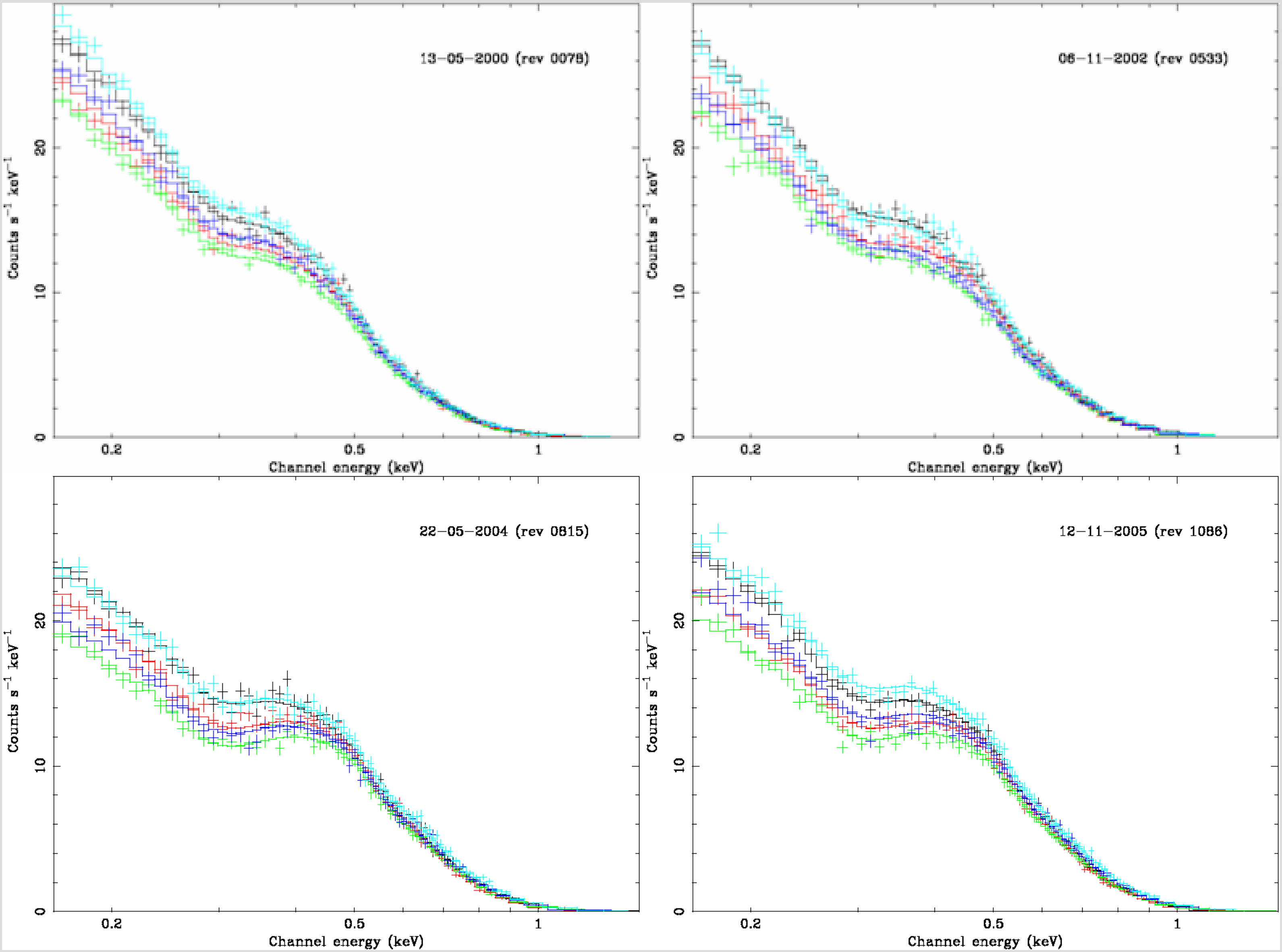
Sinusoidal variations in spectral parameters
Period 7.1 ± 0.5 years



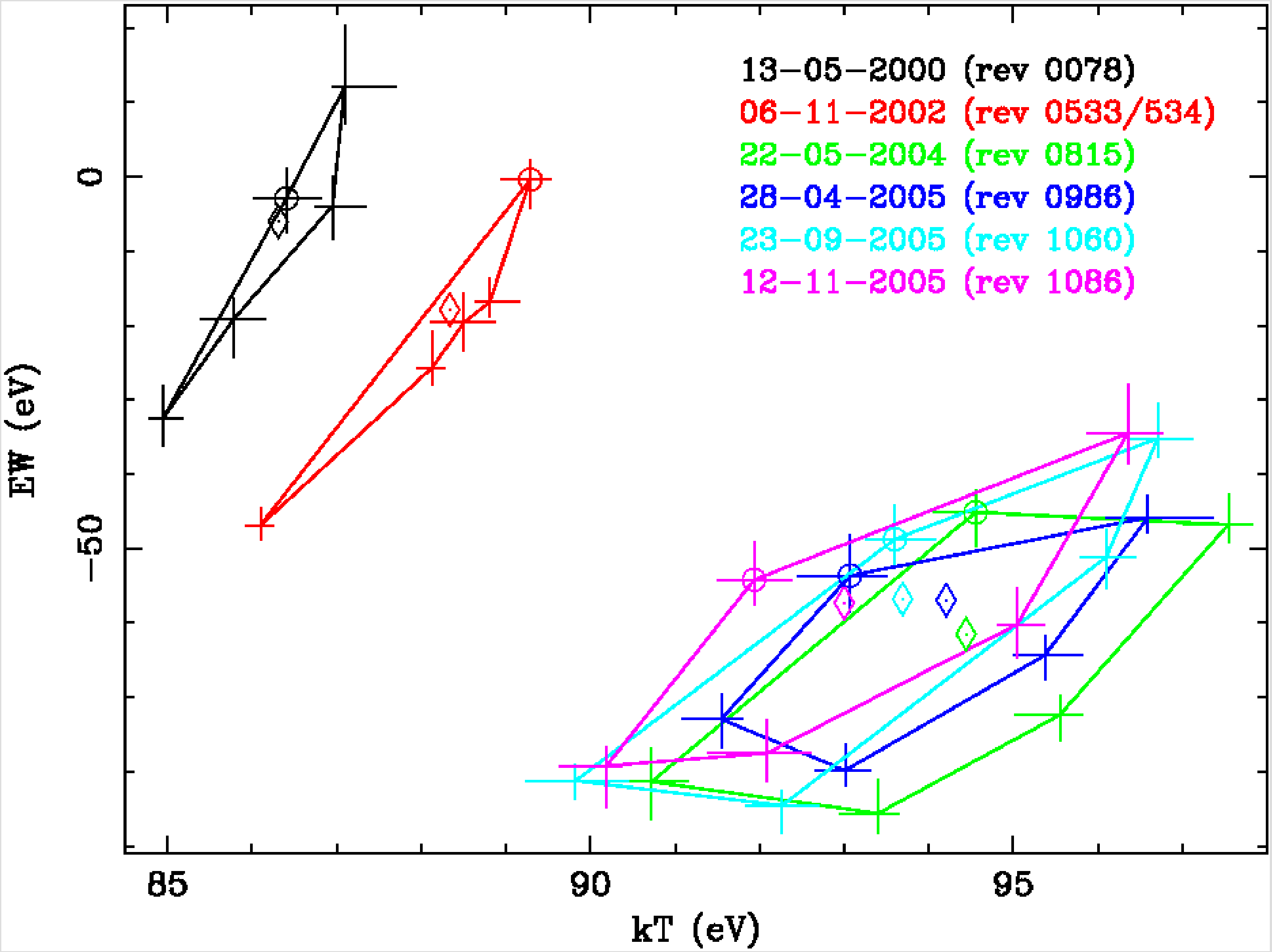
Sinusoidal variations in pulse timing
Period 7.7 ± 0.6 years

Free precession of an isolated neutron star with period 7–8 years
$\varepsilon = (I_3 - I_1) / I_1 = P_{spin} / P_{prec} \approx 4 \cdot 10^{-8}$ (moments of inertia for a rigid body)
between that reported from of radio pulsars and Her X-1

RX J0720.4-3125 pulse phase spectral variations



RX J0720.4-3125: Spectral variations over pulse and precession phase



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

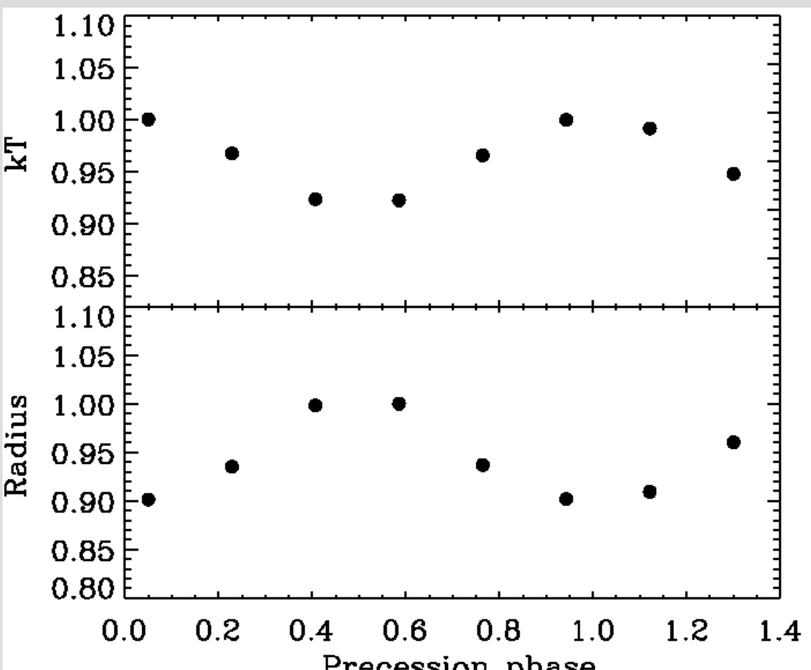
$T_1 = 80$ eV $\sin\theta_1 = 0.8$

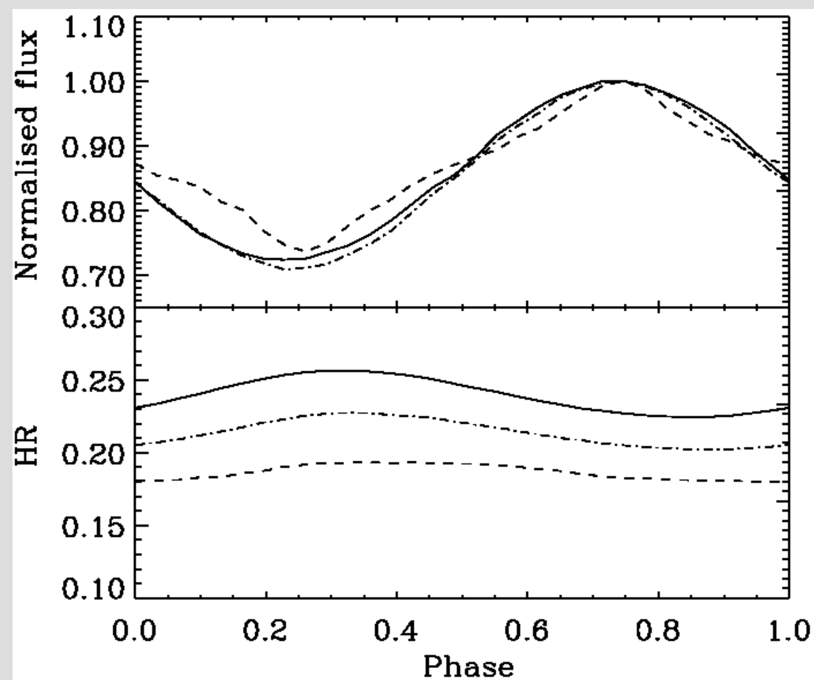
$T_2 = 100$ eV $\sin\theta_2 = 0.6$

not exactly antipodal:

phase shift of lag between hard and soft emission

$\theta_0 = 160^o$



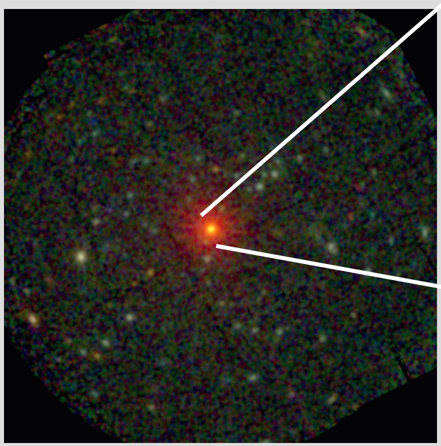


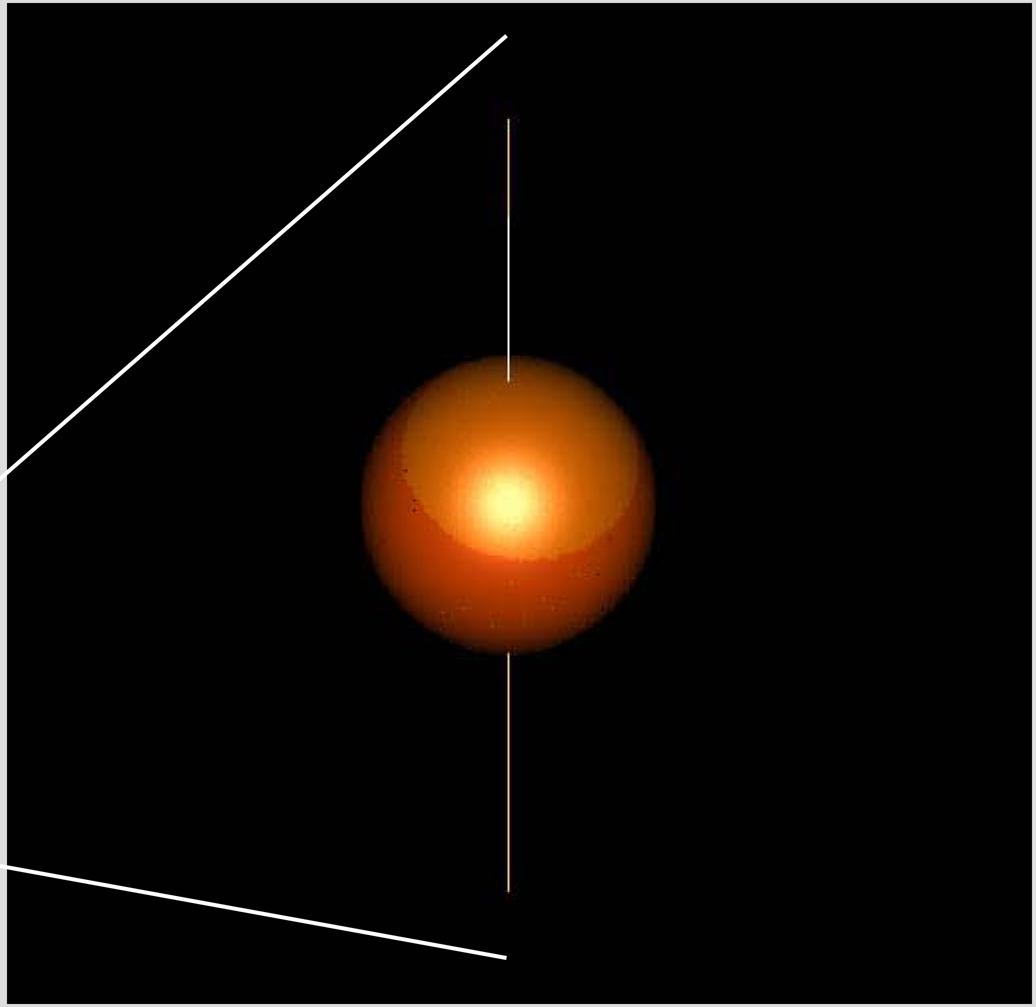
See also: Perez-Azorin et al. (2006)

RX J0720.4-3125: A precessing isolated neutron star

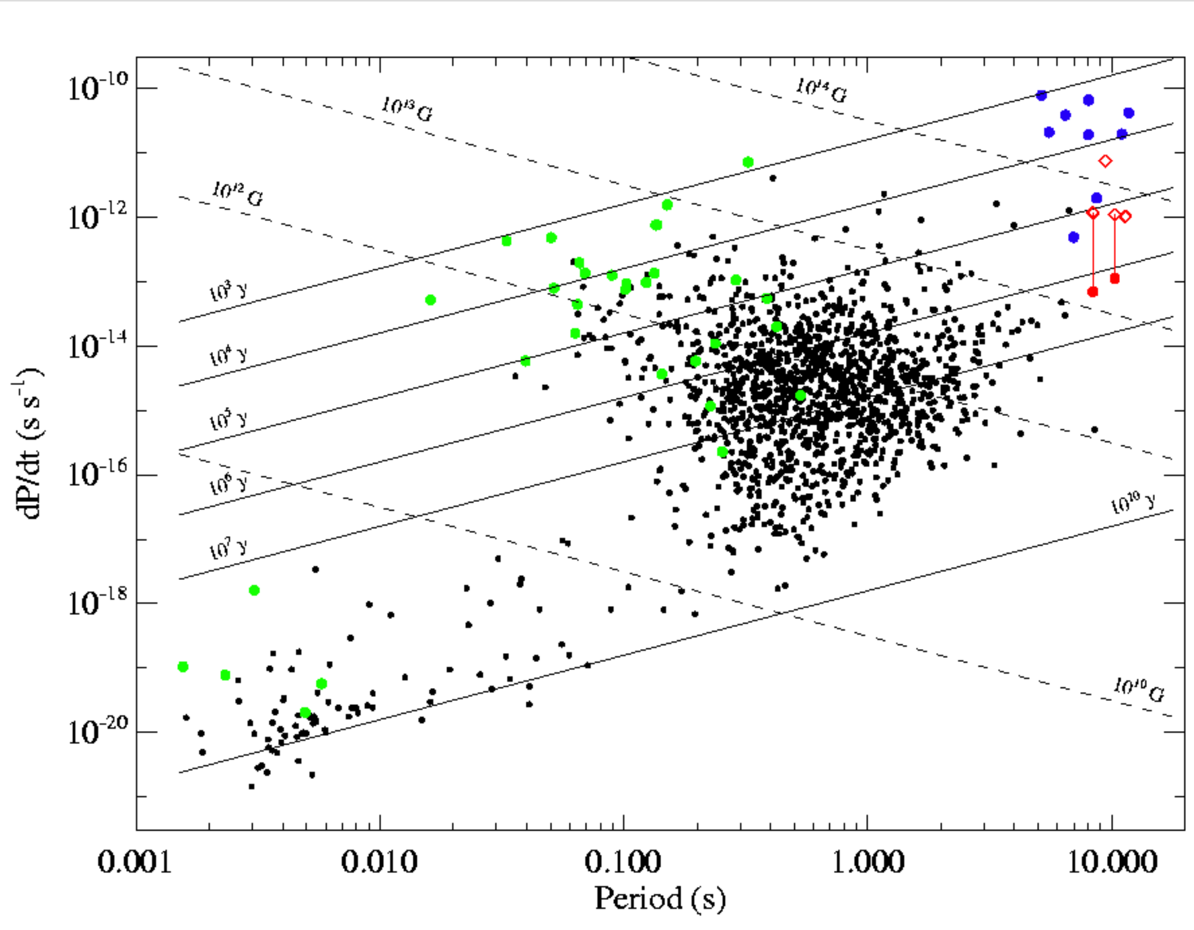
Roberto Turolla
Cor P. De Vries
Silvia Zane
Jacco Fink
Mariano Mendez
Frank Verbunt

Haberl et al. 2006
A&A 451, L17





Pulsars



high-energy detections (incomplete)

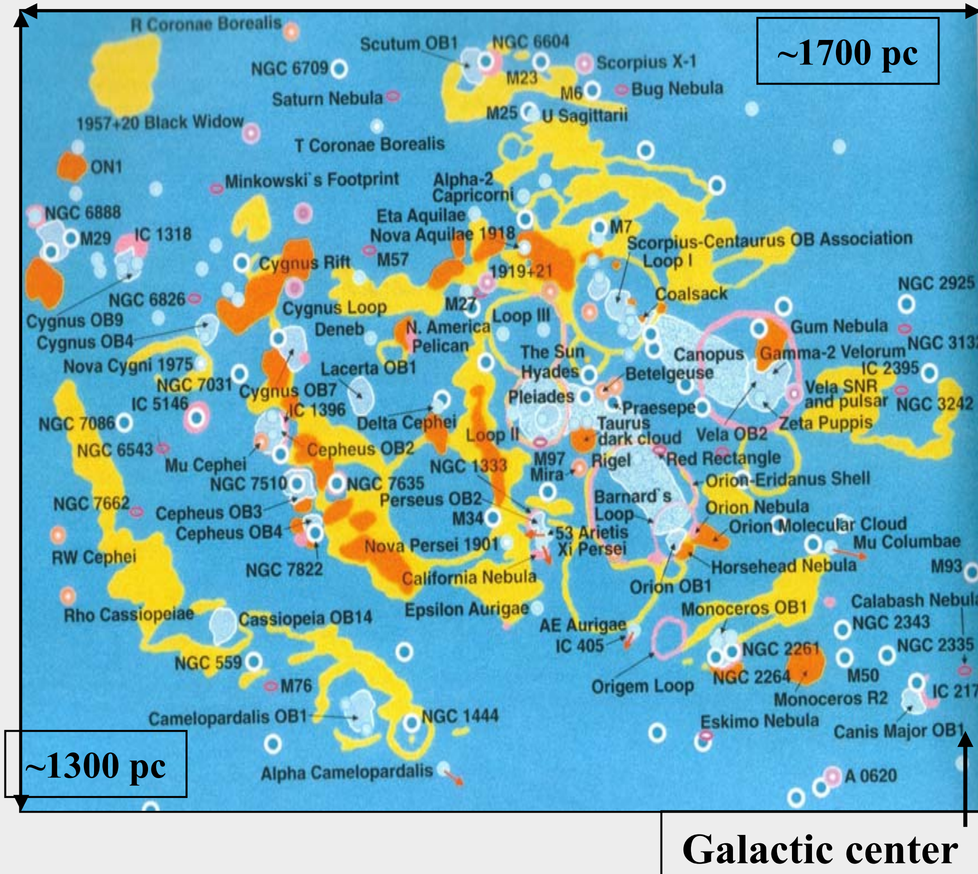
AXPs / SGRs (magnetars)

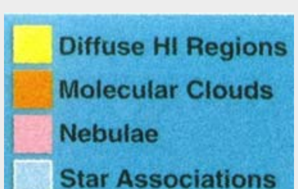
Magnificent Seven:
circles: $P/\dot{P}$
diamonds: cyclotron lines

magnetic dipole braking: age = $P / 2\dot{P}$, $B = 3.2 \times 10^{19} (P\dot{P})^{1/2}$

The inhomogenous Interstellar Medium (B. Posselt)

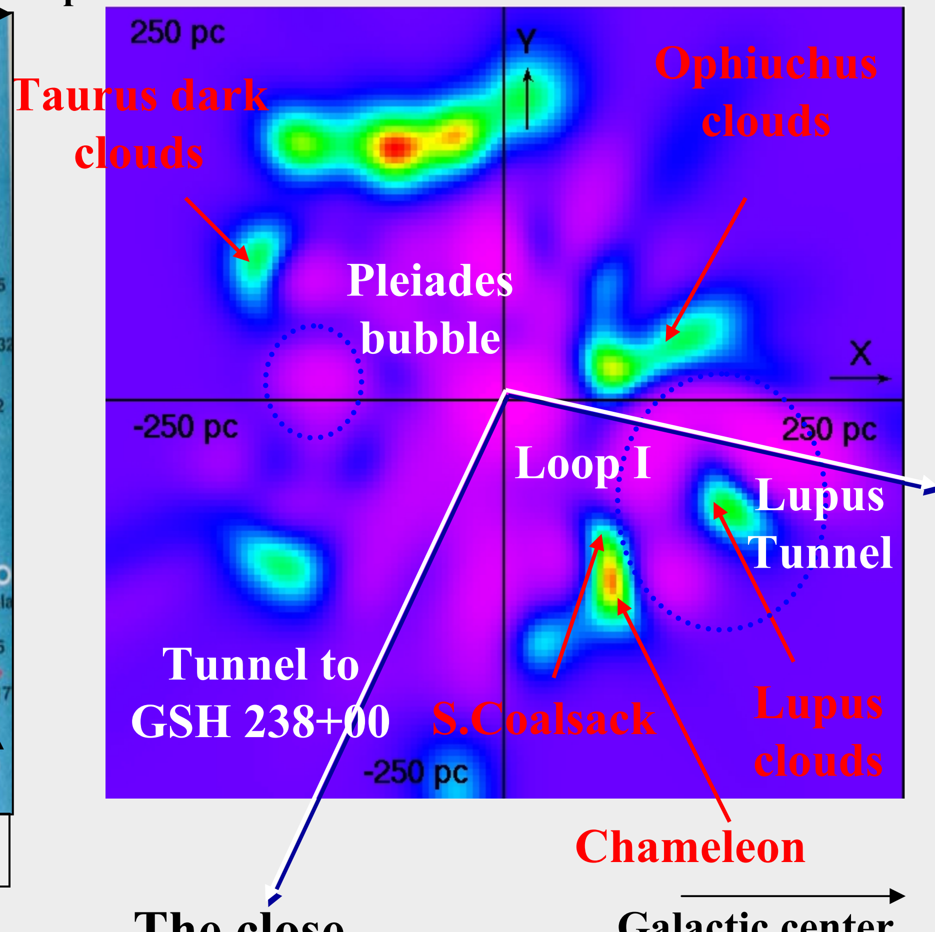
Henbest & Couper 1994





Within one kpc
around the sun

Lallement et al. 2003 (NaD)
Breitschwerdt et al. 2005



The close
solar neighbourhood

Distance estimates from X-ray absorption

In the direction of RX J1856.5-3754

(l = 359°, b = –17°)

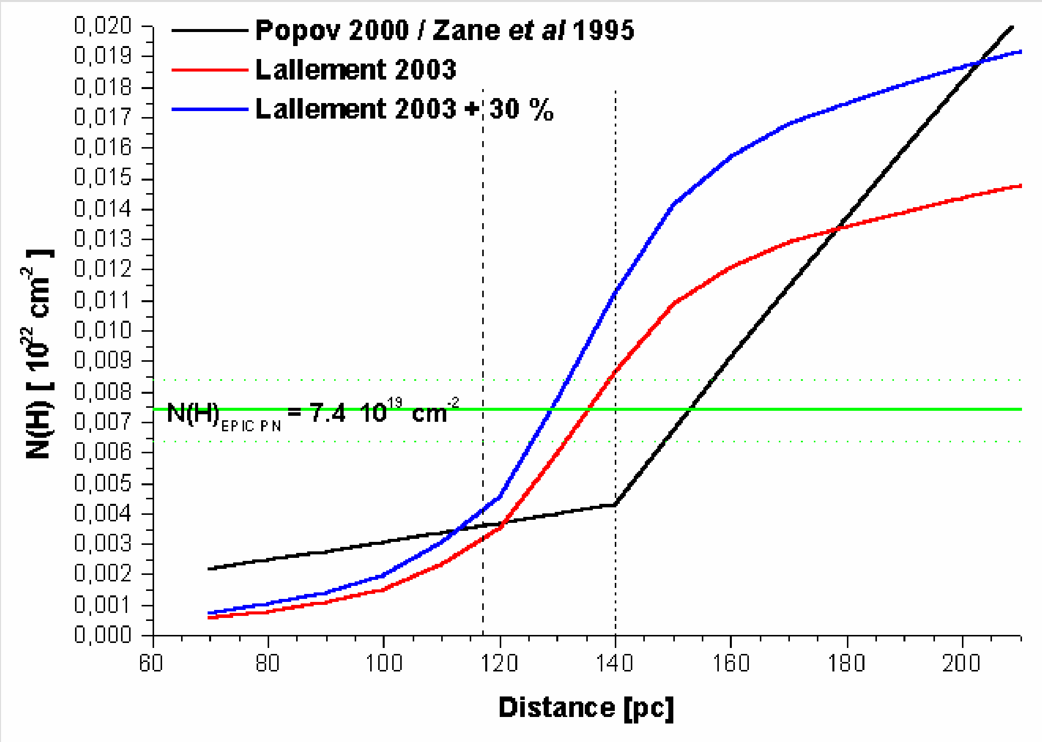
Kaplan et al. 2002 : 140 ± 40 pc

Kerkwijk & Kaplan 2006 : 147–179 pc

towards R CrA

@ 130 pc : 0.7 x 10^{20} cm^{-2}

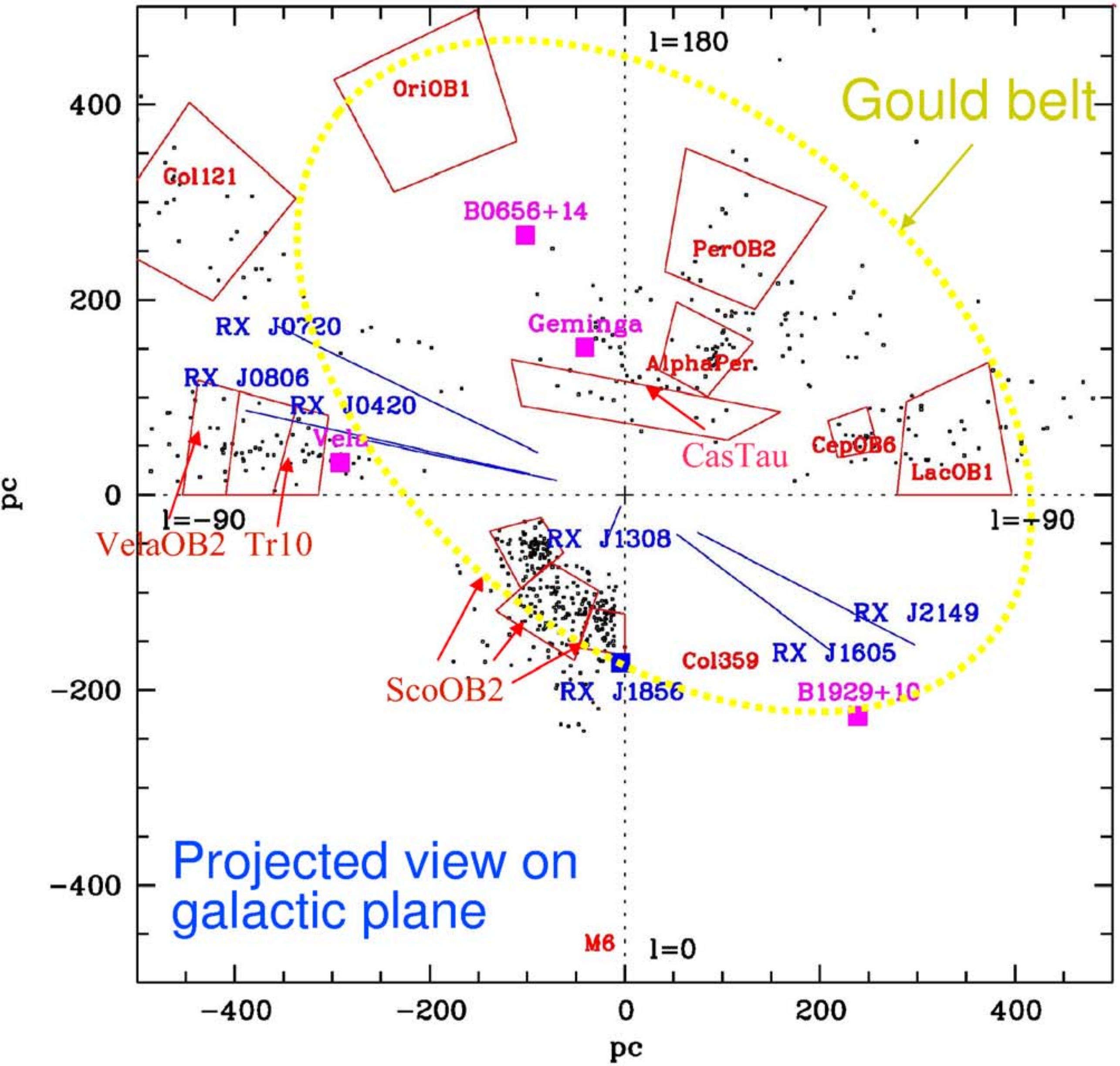
@ 140 pc : 1.0 x 10^{20} cm^{-2}



	N(H) [$10^{20}$$cm^{-2}$]	Distance [pc]
RX J1856.5-3754	0.7 (0L)	120-140
RX J0420.0-5022	1.6 (1L)	320-350
RX J0720.4-3125	1.2 (1L)	230-280
RX J0806.4-4123	1.0 (1L)	230-260
RBS 1223	4.3 (1L)	-
RX J1605.3+3249	2.0 (3L)	320-400
RBS 1774	2.4 (1L)	380-440

Posselt et al. 2006, London (astro-ph/0609275)

Nearby INS and local stellar structures



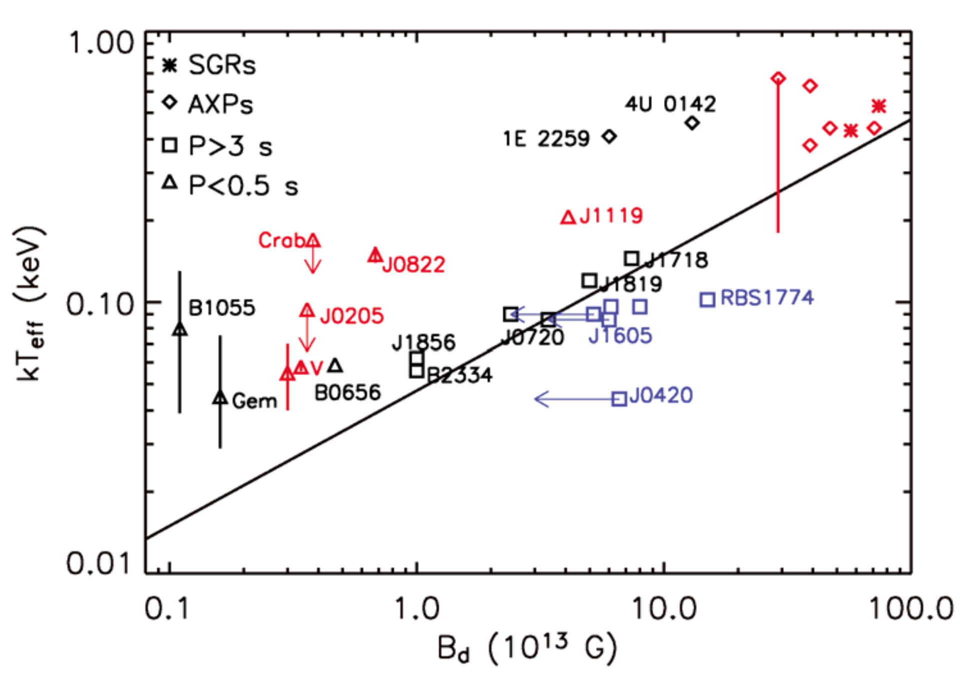
Blue lines are possible INS positions assuming d = 100 - 400 pc

OB member locations after de Zeeuw et al. 1999

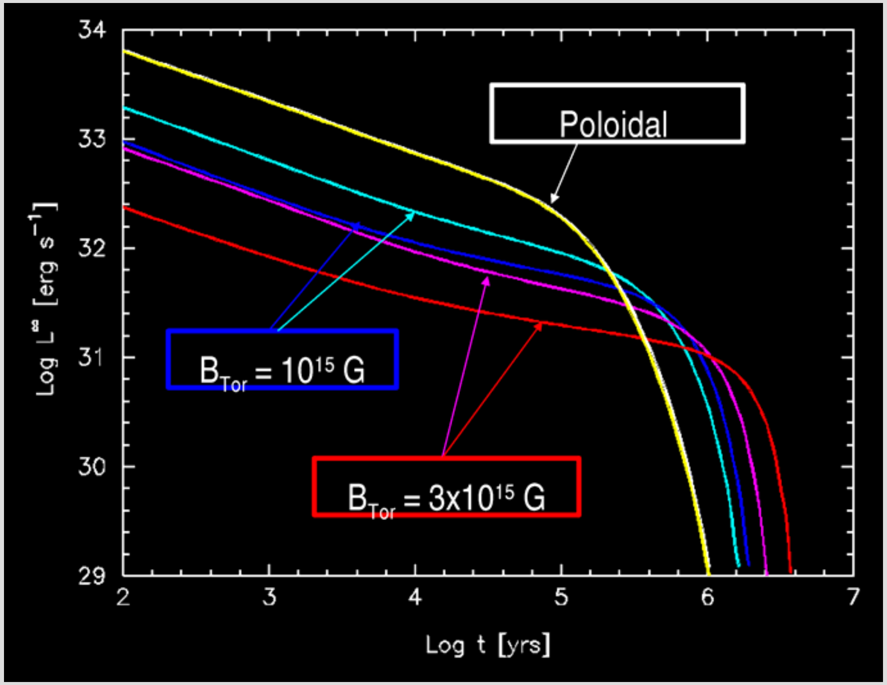
All XDINSs are located in a half sky centred on Sco OB2

Where are the nearby Neutron Stars with 10^{12} Gauss?

Pons et al. 2007 (astro-ph/0607583)



Page et al. 2007 (astro-ph/0701442)



- **Heating by field decay?**
- **Lower overall cooling rate?**
- **Hotter polar caps?**

The Magnificent Seven: Summary

$F_x/F_{opt} > 10^4$ → Isolated neutron stars
High proper motion → Nearby, cooling isolated neutron stars
dP/dt + absorption features → Magnetic fields $10^{13\text{-}14}$ G
Evidence for multiple lines → Proton cyclotron absorption
+ Atomic line transitions?

Interesting individuals:
RX J0720.4-3125: Pulsar, absorption feature → B field, kT distribution
Precession → A probe to the NS interior
RX J1856.4-3754: Weak pulsations, no absorption feature

State of the atmosphere (condensed)?
Composition of the atmosphere?
Origin of absorption features?
Individual differences (viewing effects) ?

Theoretical work on NS atmospheres (strong B fields)
Improved X-ray detectors (resolution + sensitivity)
X-ray monitoring
More optical observations (large telescopes)