Nearby radio-quiet isolated neutron stars with strong magnetic fields

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Magnetic field estimates

- **X-ray pulsations**
  - **Spin period history**
- **X-ray spectrum**
  - **Absorption features**
    - **Variations with pulse phase**
    - **Variations on long-term time scales**
    - **Cyclotron lines – Harmonics ?**
    - **Atomic transition lines ?**

Neutron Stars at the Crossroads of Fundamental Physics

Vancouver, Canada, 9-13 August 2005

Thermal, radio-quiet isolated neutron stars

- Soft X-ray sources in ROSAT survey
- Blackbody-like X-ray spectra, NO non-thermal hard emission
- Low absorption ~10^{20} H cm^{-2}, nearby, parallax for RX J1856.5-3754: 117 pc
- Luminosity ~10^{31} erg s^{-1} (dim)
- Constant X-ray flux on time scales of years (RX J0720.4–3125 ?)
- No obvious association with SNR
- No radio emission
- Optically faint
- Some (all?) are X-ray pulsars (3.45 – 11.37 s)

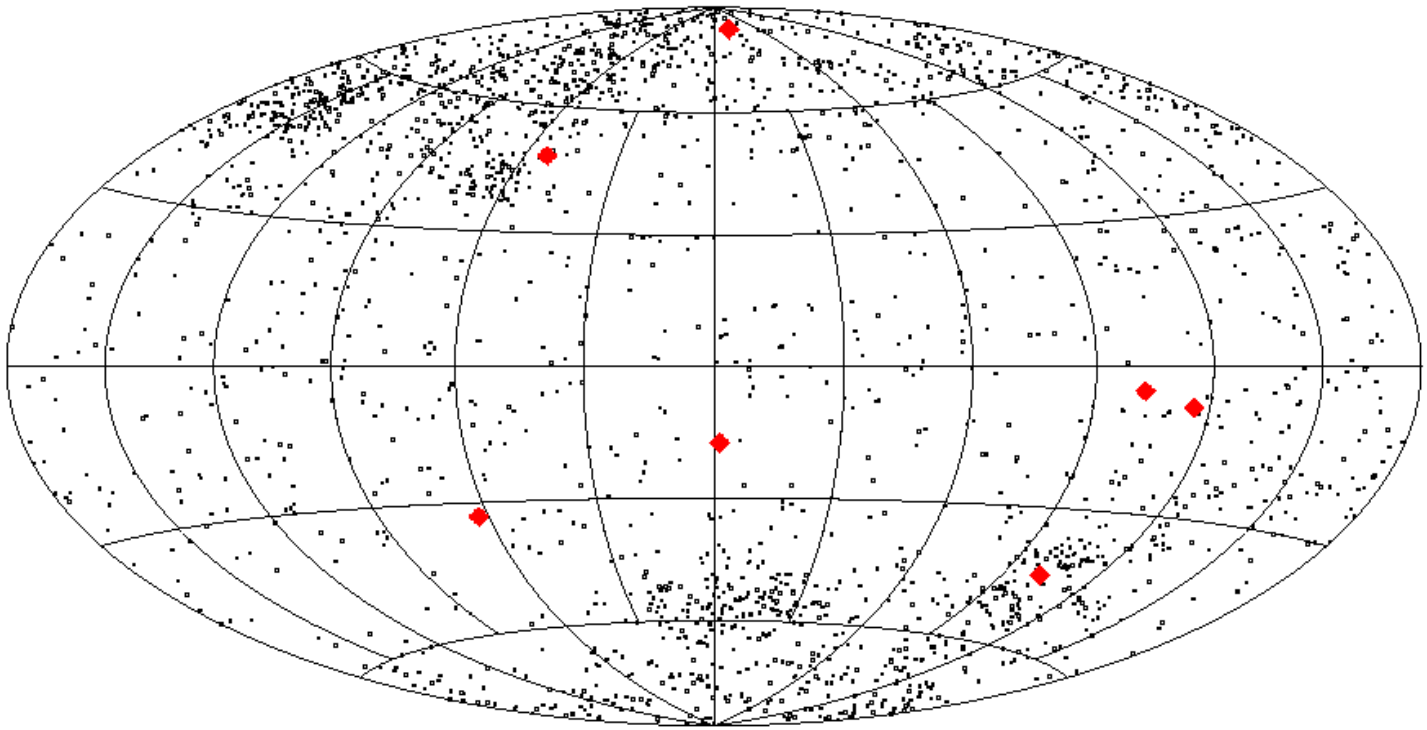
best candidates for „genuine“ INSs with undisturbed emission from stellar surface

Object	kT/eV	P/s	Optical	
RX J0420.0–5022	44	3.45	B = 26.6	
RX J0720.4–3125	85-95	8.39	B = 26.6	PM = 97 mas/y
RX J0806.4–4123	96	11.37	B > 24	
RBS 1223 (*)	86	10.31	m_{50ccd} = 28.6	
RX J1605.3+3249	96		B = 27.2	PM = 145 mas/y
RX J1856.5–3754	60		V = 25.7	PM = 332 mas/y
RBS 1774 (**)	101	9.44	R > 23	

(*) 1RXS J130848.6+212708 (**) 1RXS J214303.7+065419

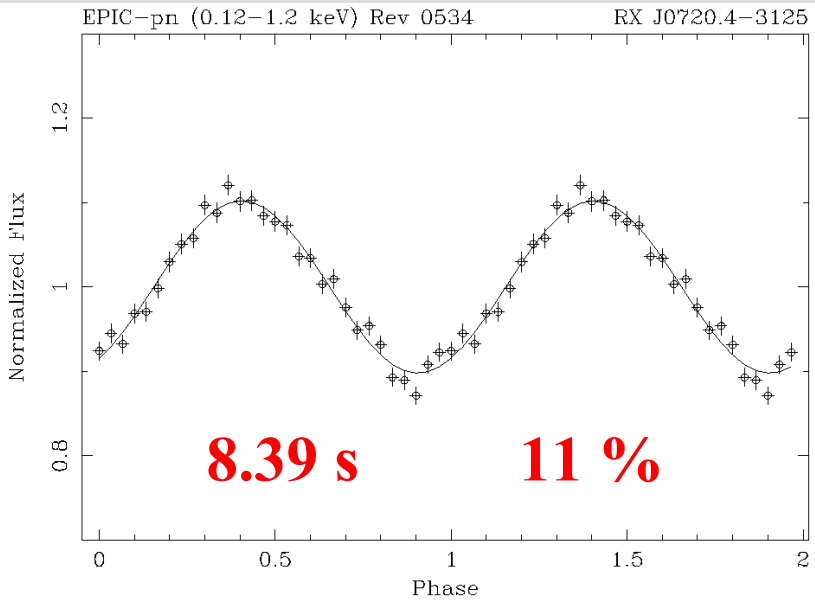
The Magnificent Seven

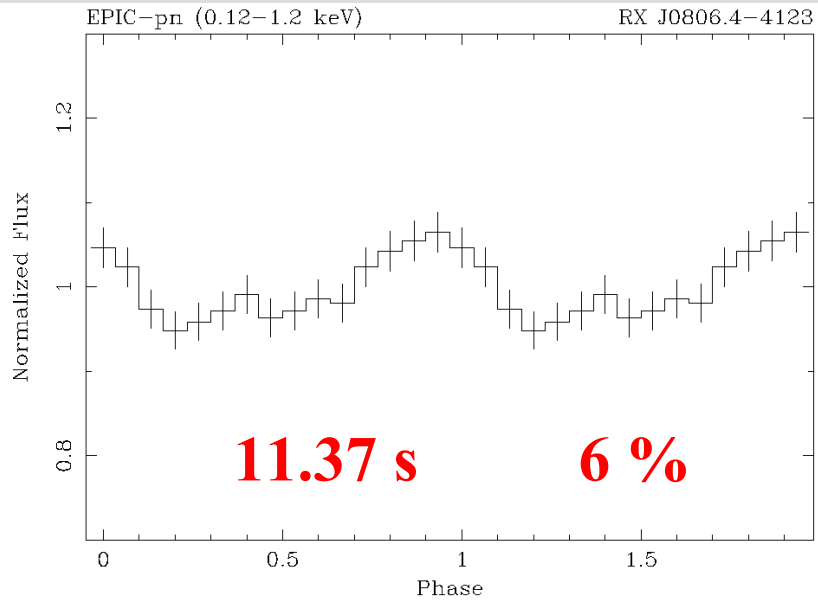
Soft X-ray spectrum + faint in optical

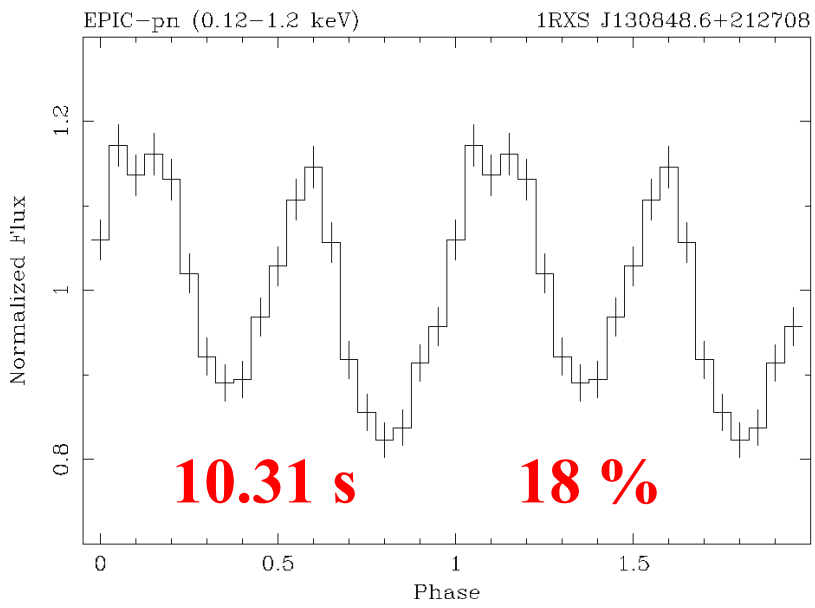


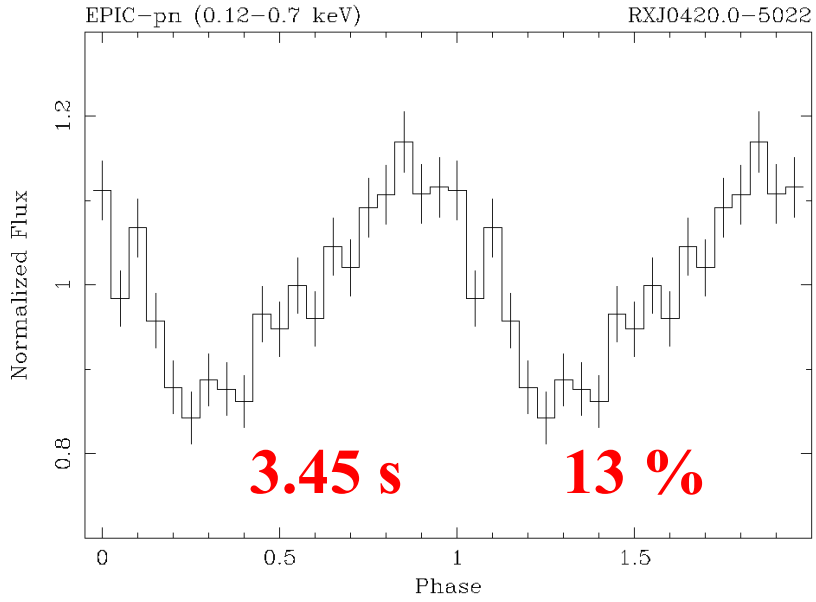
PSPC cts/s	HR1	HR2	Name
0.15 ± 0.01	-0.96 ± 0.03	-0.45 ± 0.73	RX J0420.0-5022
0.23 ± 0.03	-0.06 ± 0.12	-0.60 ± 0.17	RBS1774 = 1RXS J214303.7+065419
0.29 ± 0.02	-0.20 ± 0.08	-0.51 ± 0.11	RBS1223 = 1RXS J130848.6+212708
0.38 ± 0.03	-0.74 ± 0.02	-0.66 ± 0.08	RX J0806.4-4123
0.78 ± 0.02	-0.67 ± 0.02	-0.68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

X-ray pulsations

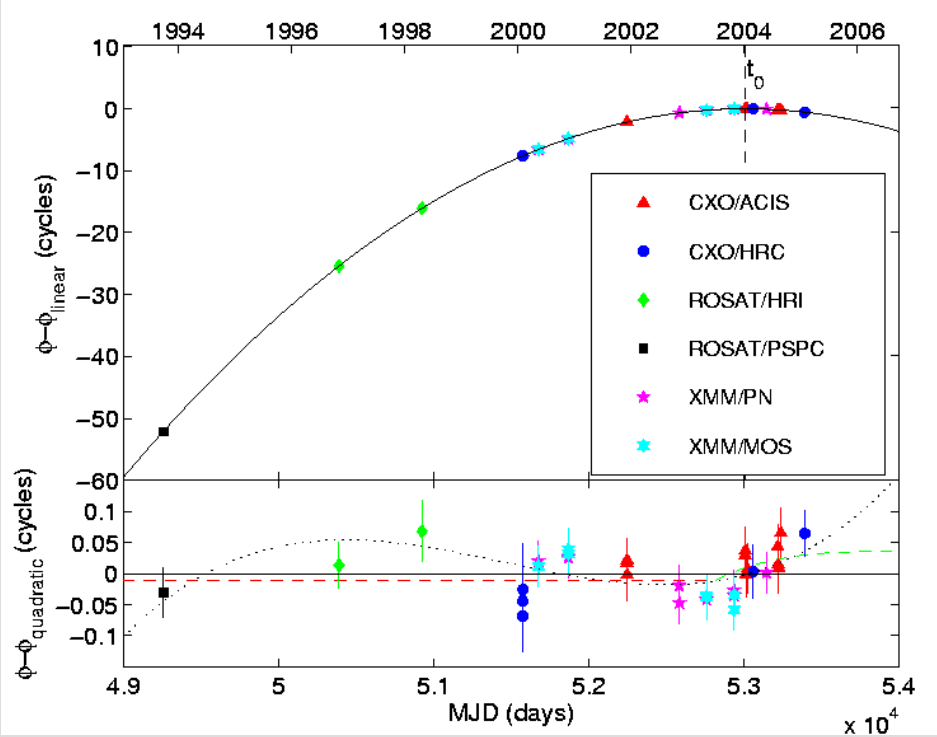








Period history: RX J0720.4–3125 and RBS 1223



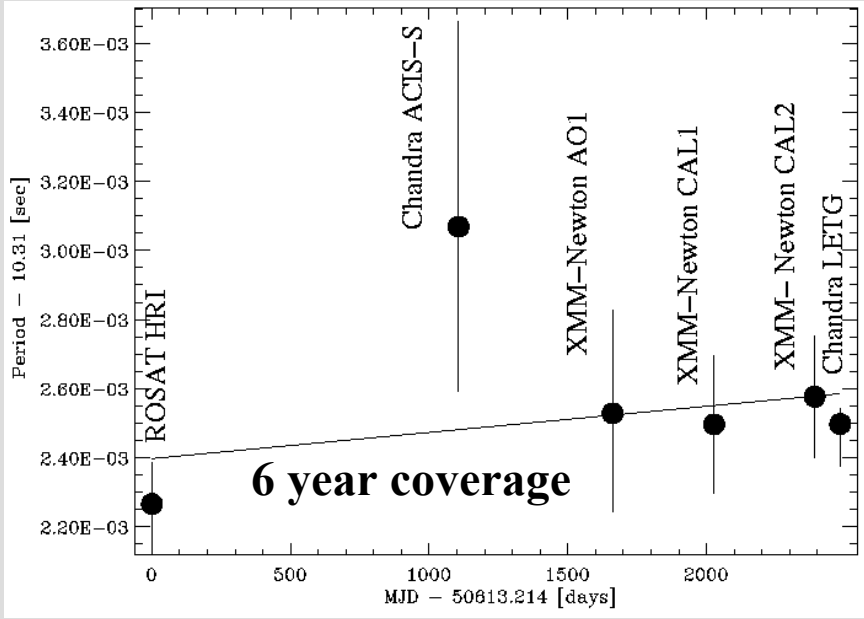
P = 8.39 s

dP/dt = (6.98 ± 0.02) x 10^{-14} s s^{-1}

τ = P/2(dP/dt) = 1.9 x 10^{6} y

B = 2.4 x 10^{13} G

Kaplan & van Kerkwijk 2005
ApJ 628, L45



P = 10.32 s

spin evolution still unclear

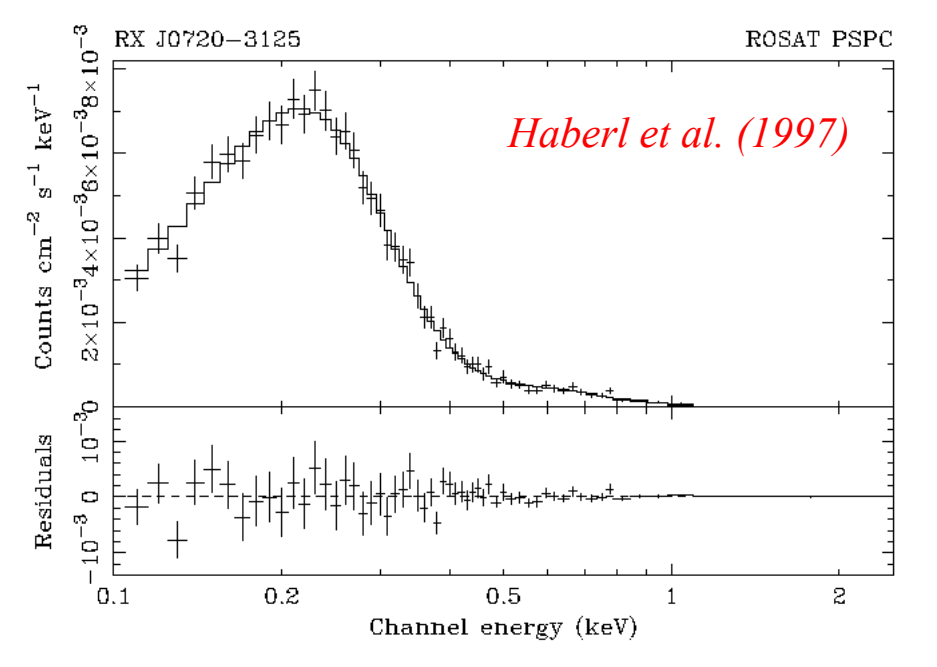
conservative upper limit:

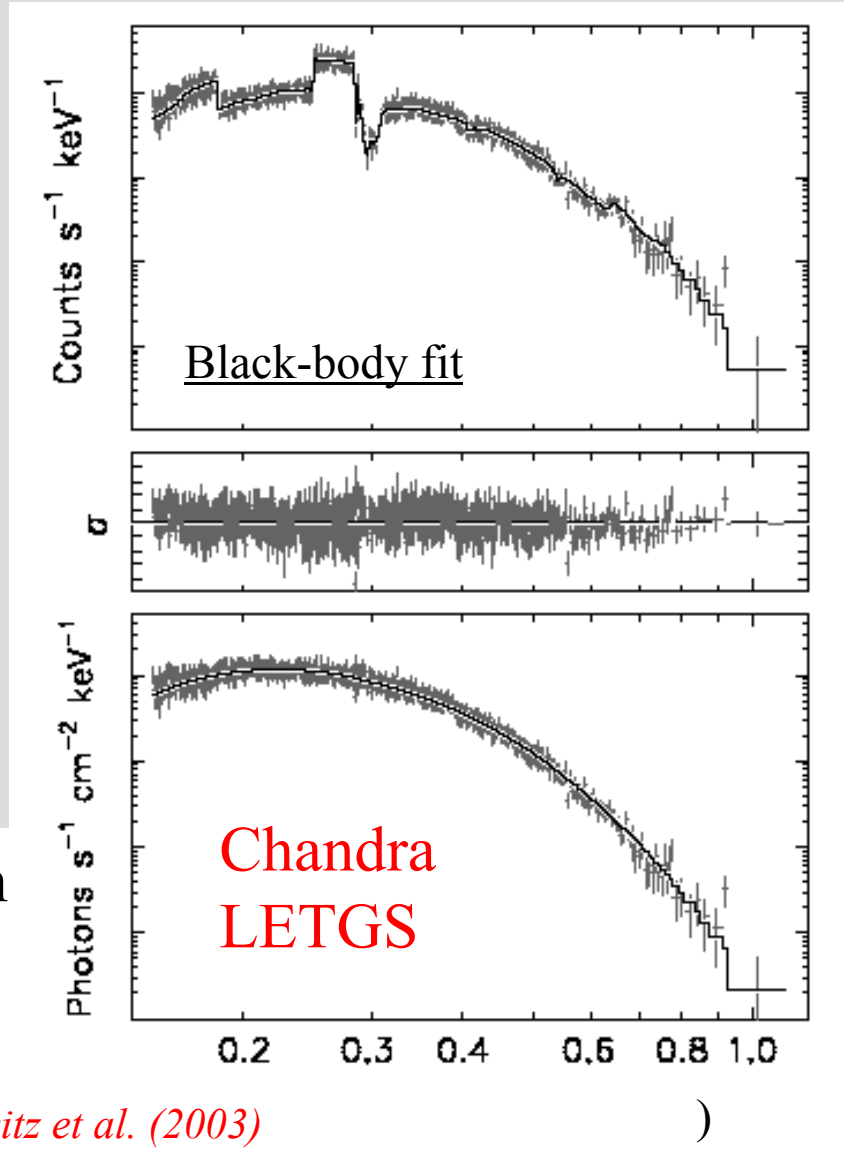
dP/dt < 9 x 10^{-13} s s^{-1}

B < 10^{14} G

Schwope et al. 2005, A&A in press

Soft, thermal X-ray spectra





n_H = (9.5 ± 0.03) x 10^{19} cm

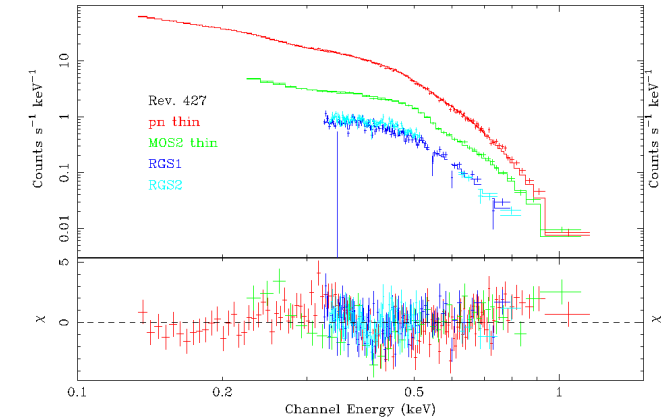
kT_∞ = 63.5 ± 0.2 eV

R_∞ = 4.4 ± 0.1 km (120pc)

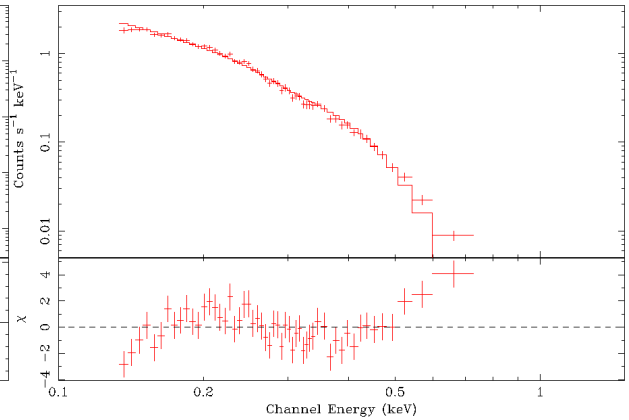
L_{bol} = 4.1 x 10^{31} erg s^{-1} *Burwitz et al. (2003)*

X-ray spectral survey: black-body fits

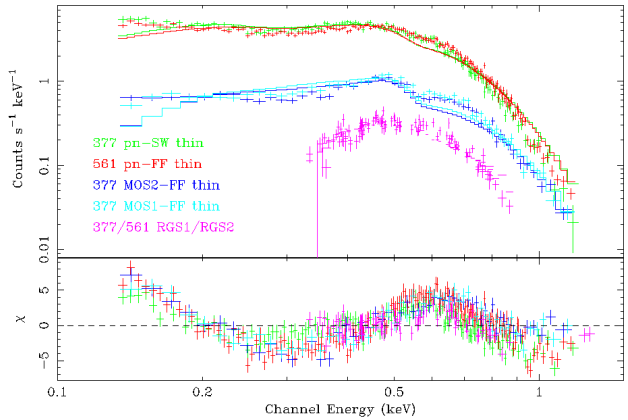
RX J1856.5–3754

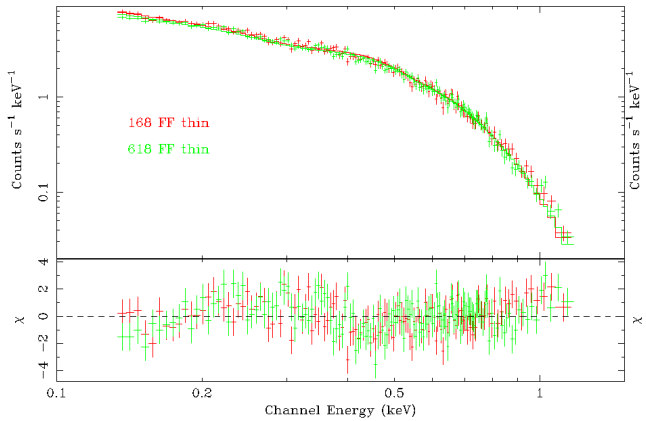


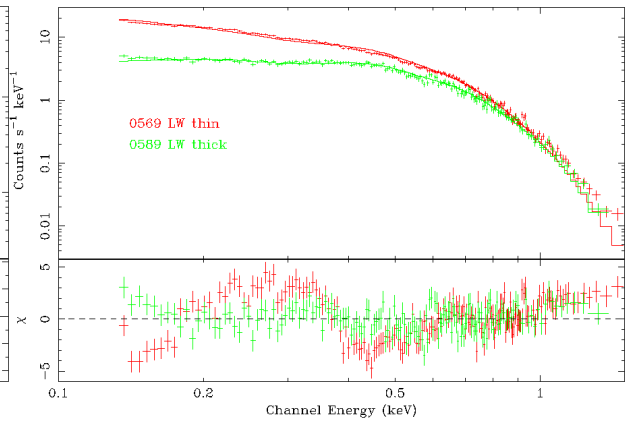
RX J0420.0–5022

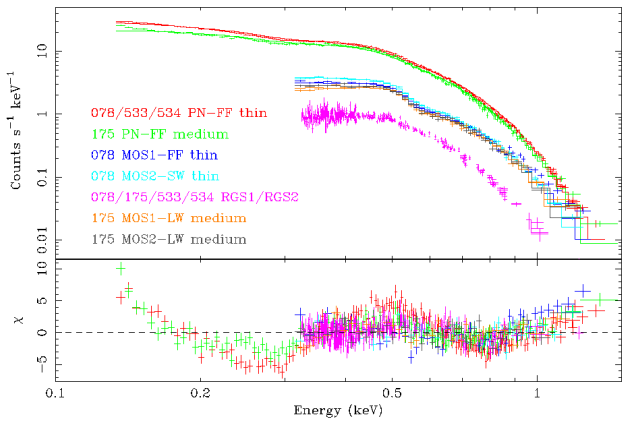


RBS 1223







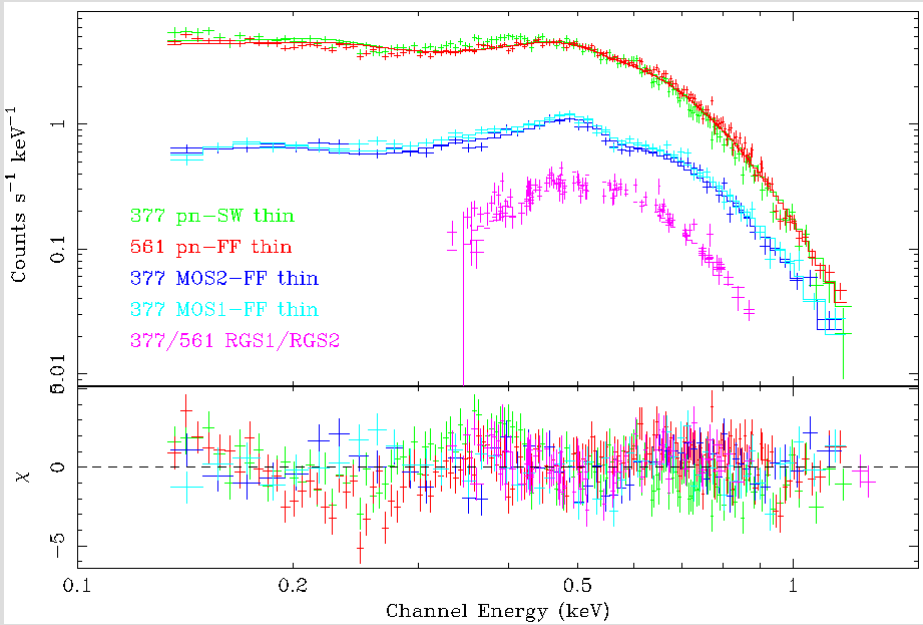


RX J0806.4–4123

RX J1605.3+3249

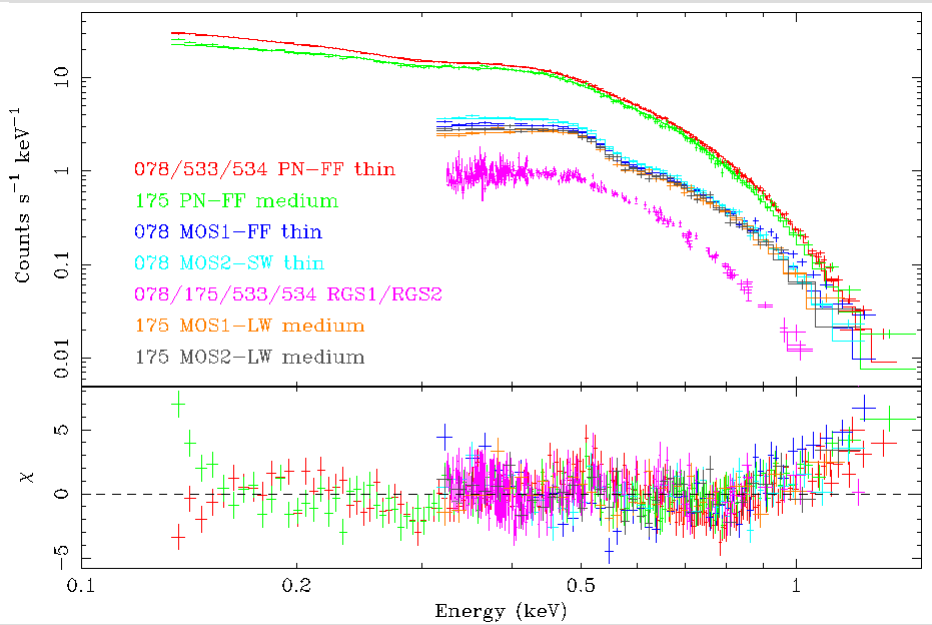
RX J0720.4–3125

X-ray spectral survey: absorption features



RBS 1223
kT = 95 eV
N_H = 7.1 x 10^{20} cm^{-2}
E_{line} ~ 300 eV
σ ~ 100 eV
EW = 150 eV

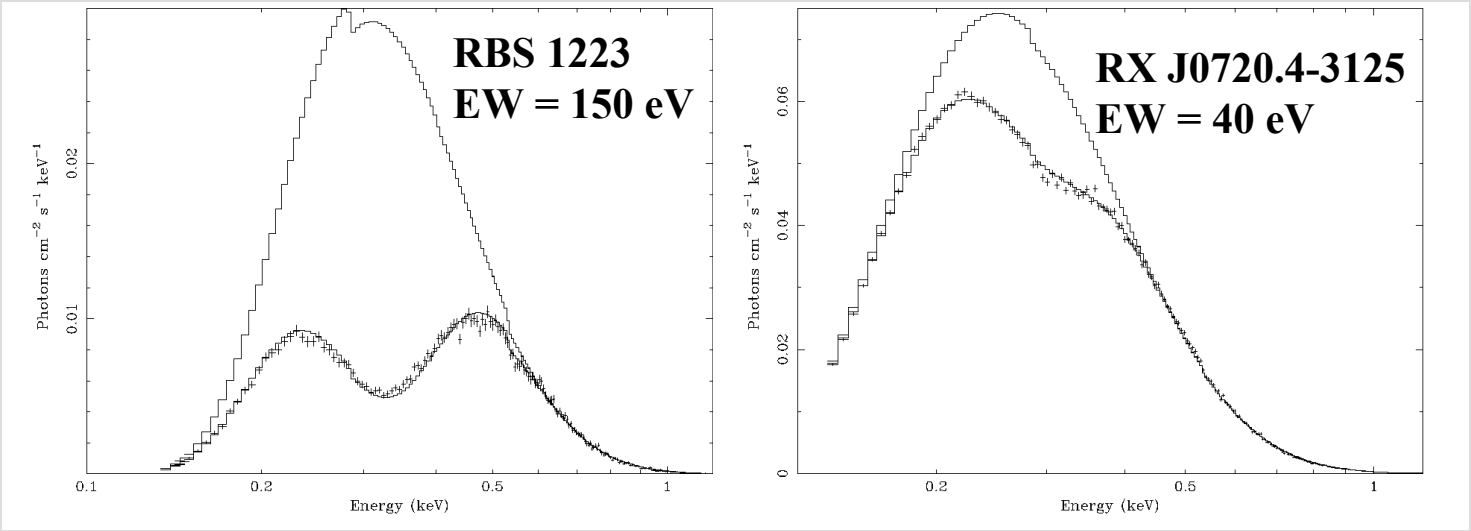
Haberl et al. (2003)

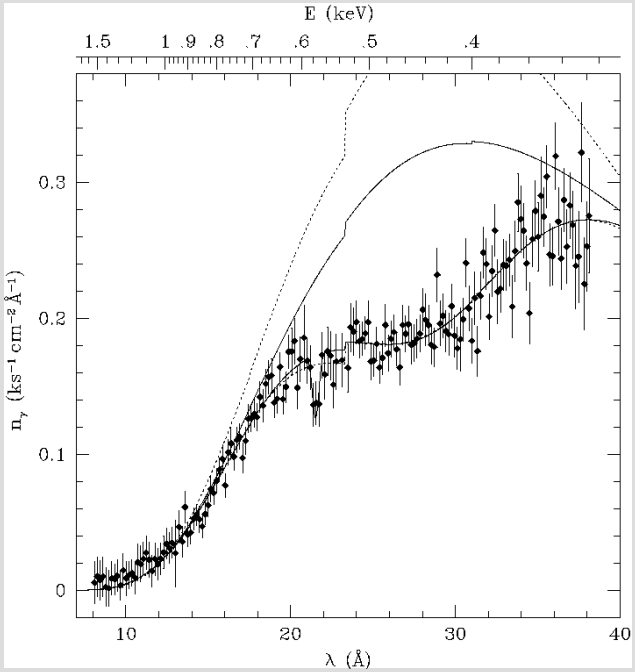


RX J0720.4-3125
kT = 85 eV
N_H = 9 x 10^{19} cm^{-2}
E_{line} = 271 ± 14 eV
σ = 66 ± 7 eV
EW = 40 eV

Haberl et al. (2004)

X-ray spectral survey: absorption features

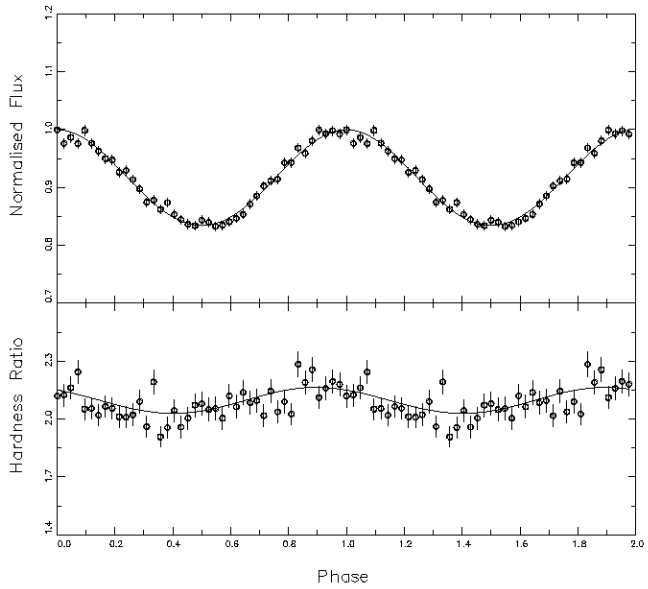


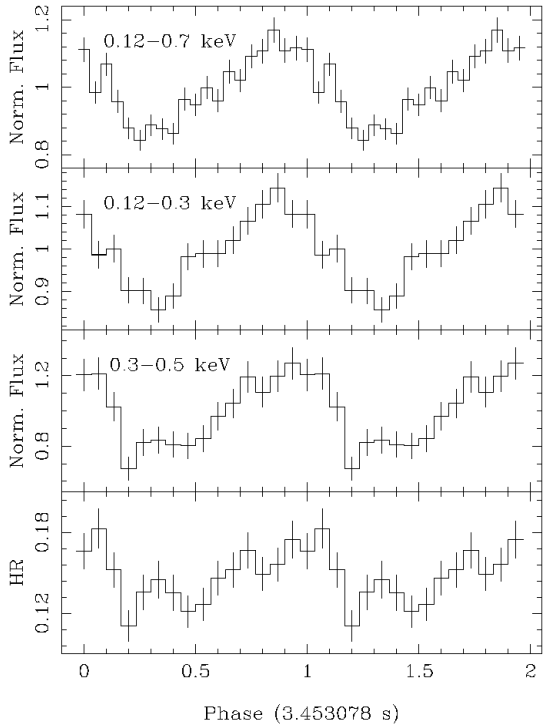


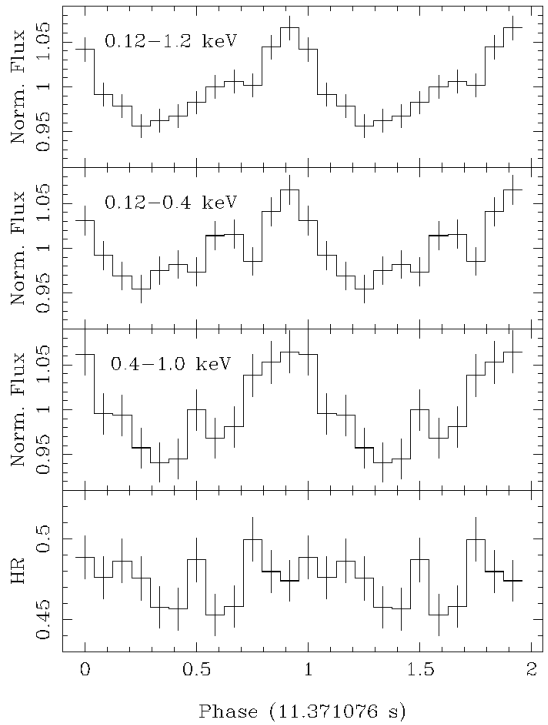
RX J1605.3+3249
RGS
kT = 95 eV
N_H = 0.8 x 10^{20} cm^{-2}
E_{line} = 450 – 480 eV

Van Kerkwijk et al. (2004)

Spectral variations with pulse phase







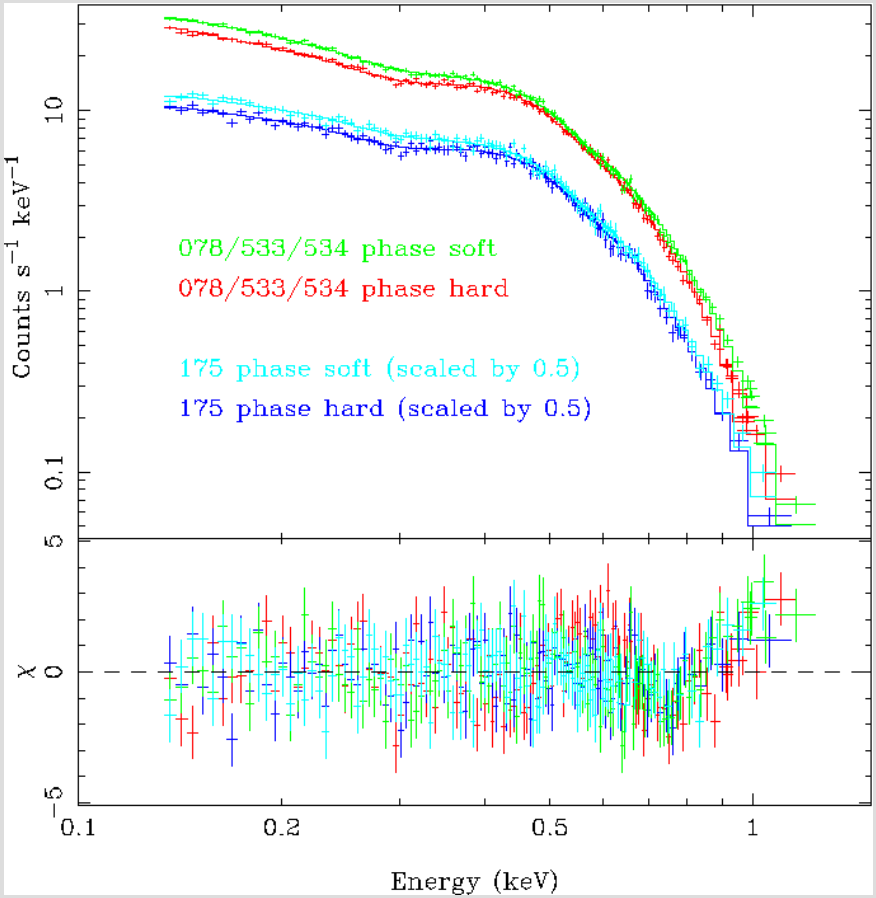
RX J0720.4-3125

Cropper et al. (2001)

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

Haberl et al. (2005)

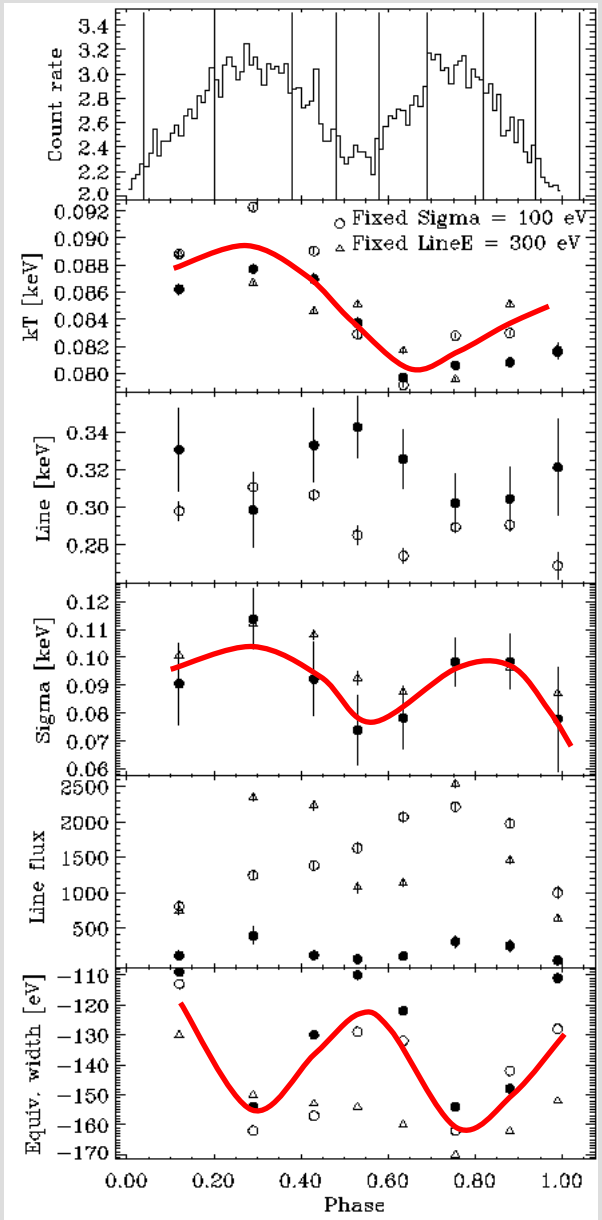
RX J0720.4-3125: Variation of absorption line with pulse phase

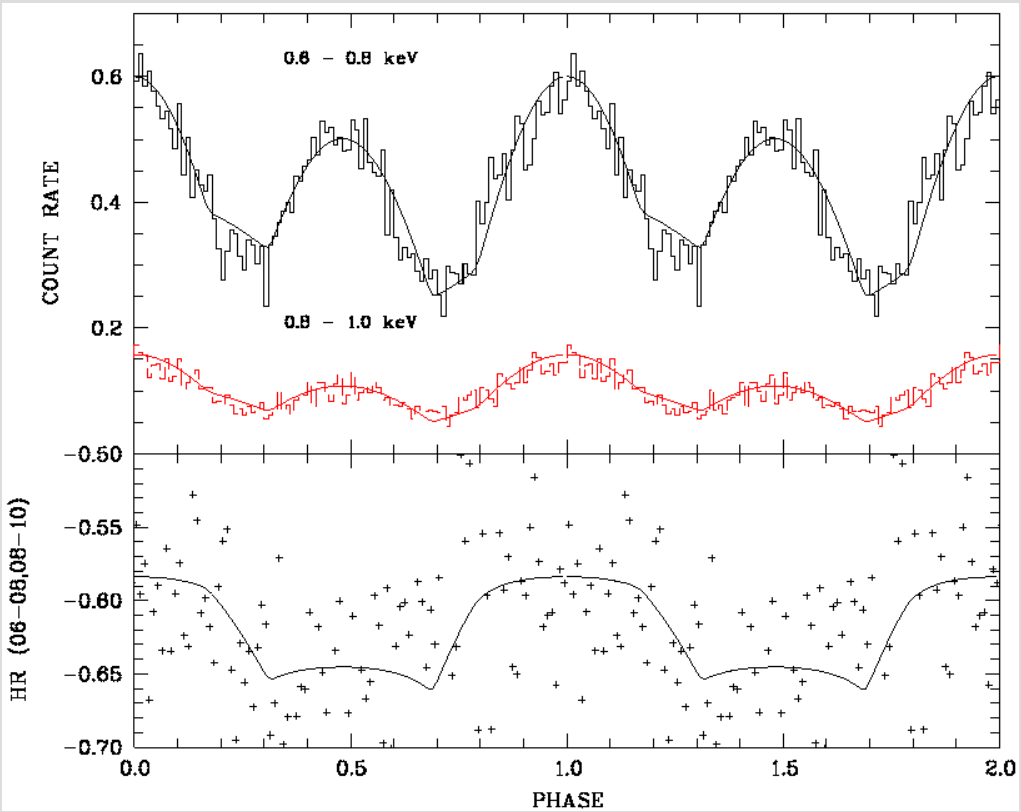


Absorption line equivalent width varies between 30 eV to 60 eV.
Small temperature variations by 2-3 eV.

Haberl et al. (2004)

Spectral variations with pulse phase





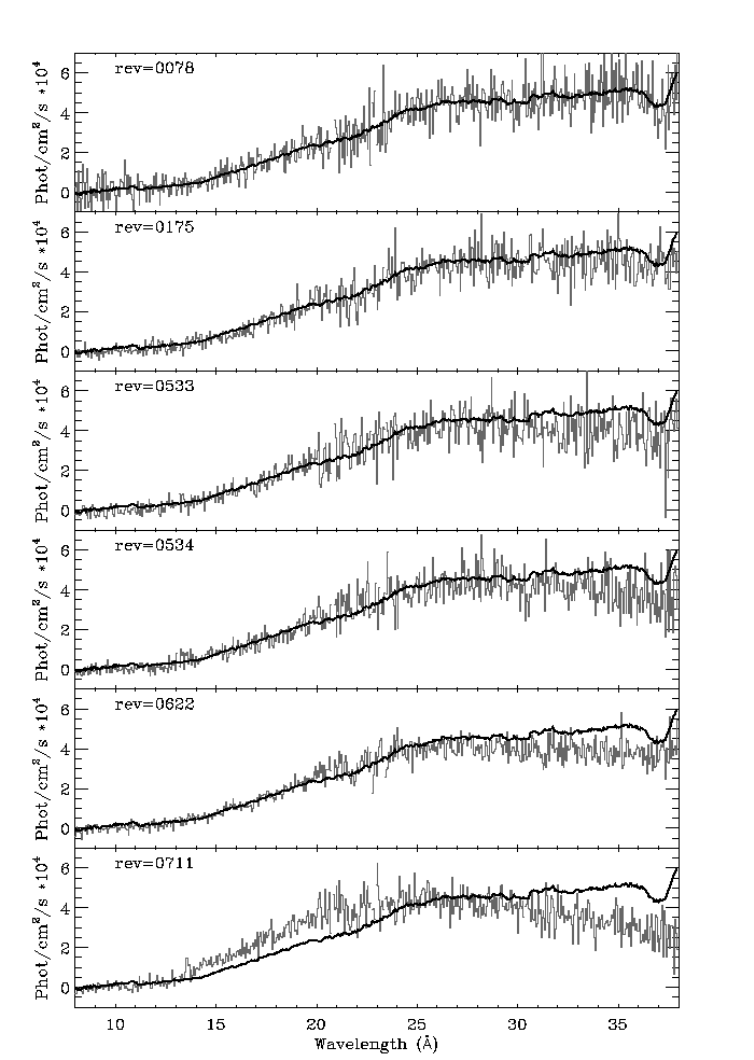
RBS 1223 (10.31s) ***Schwope et al. 2005, A&A in press***

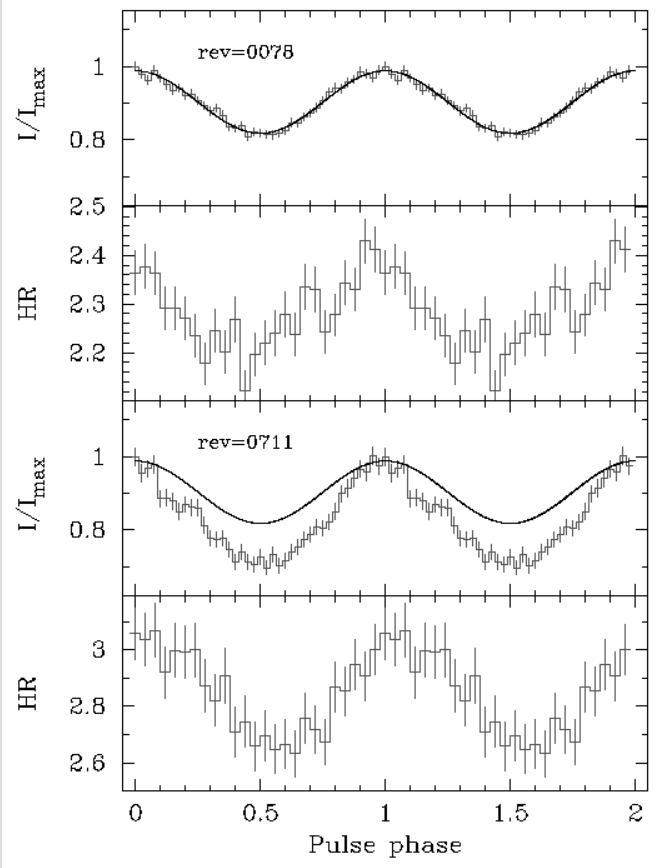
Two-spot model: kT_{∞} **= 92 eV and 84 eV**

2Φ ~ 8° and ~10°

offset ~ 20°

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

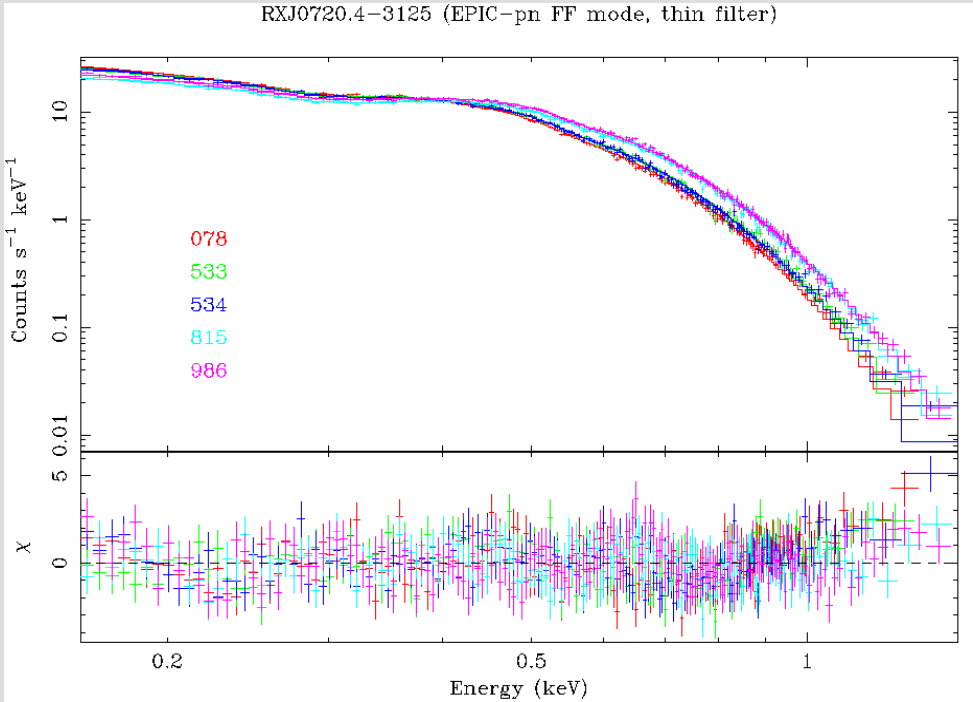




Precession of the neutron star?

de Vries et al. (2004)

RX J0720.4-3125: Variation of absorption line with time

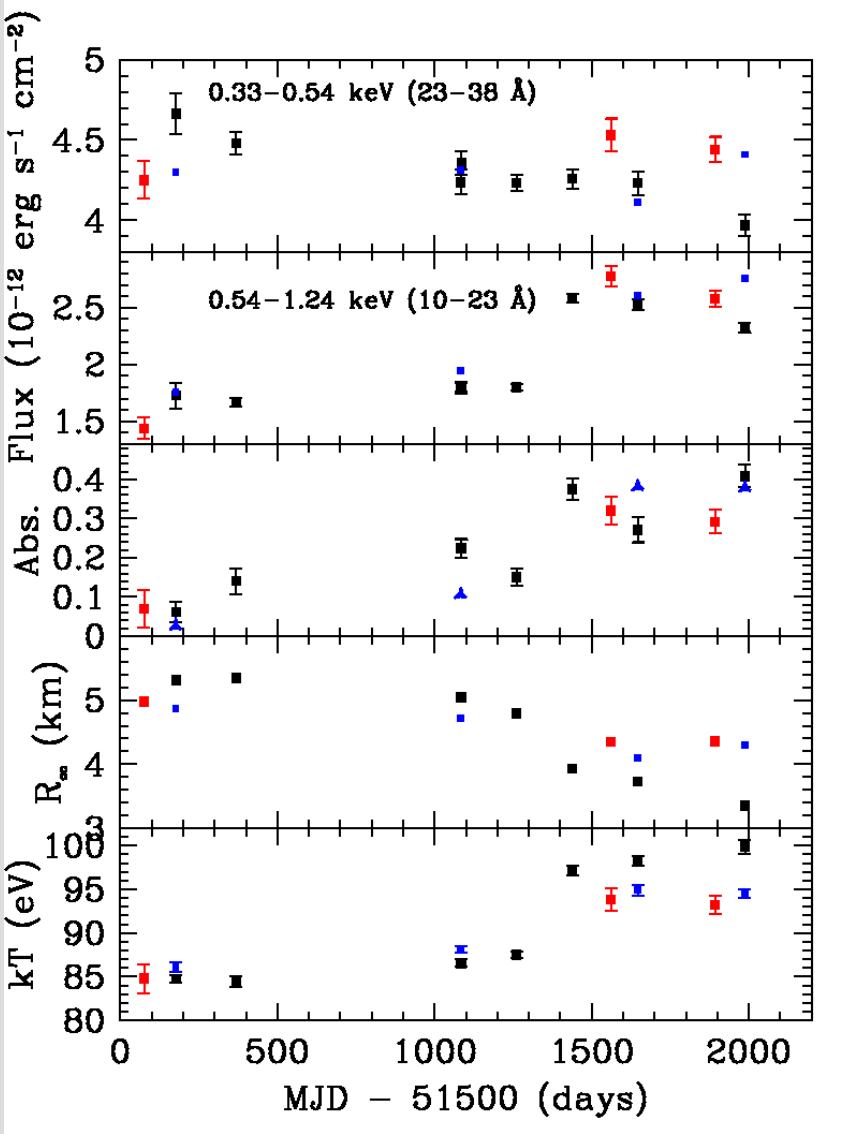


Rev.	kT(eV)	EQW(eV)
078	86.2 ± 0.5	5.6
533	88.2 ± 0.4	16.9
534	88.2	16.9
815	95.2 ± 0.4	53.5
986	94.7 ± 0.6	53.6

common line energy: 308 ± 7 eV
common line width: σ = 69 ± 5 eV

Absorption line equivalent width varies by a factor of 10 over 5 years.
Temperature variations by 8.5 eV.

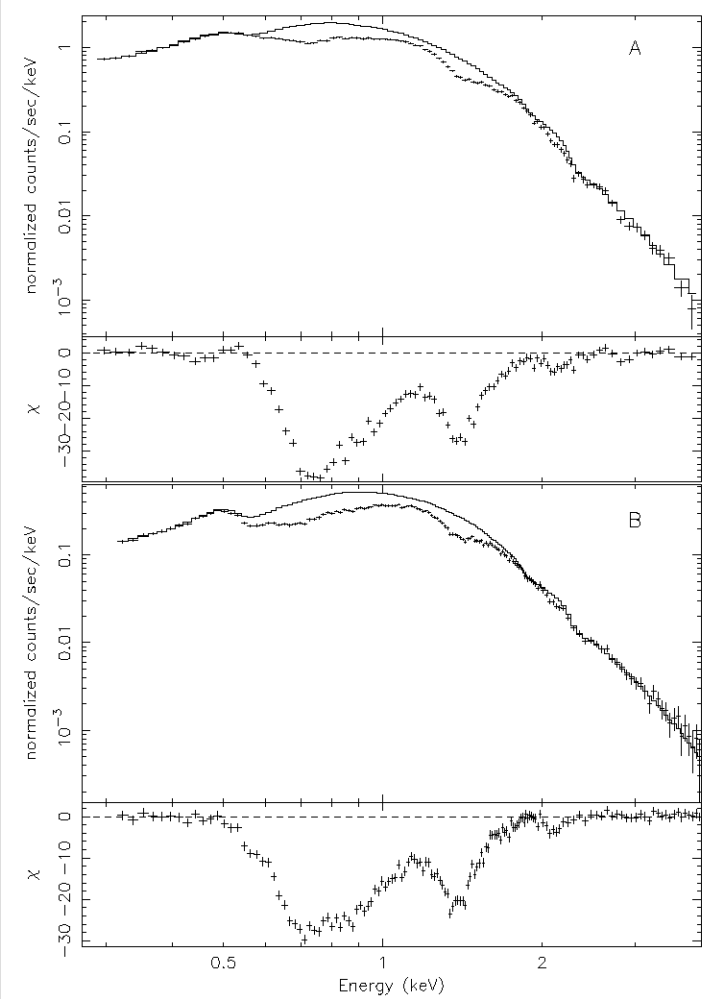
RX J0720.4-3125: History of spectral evolution

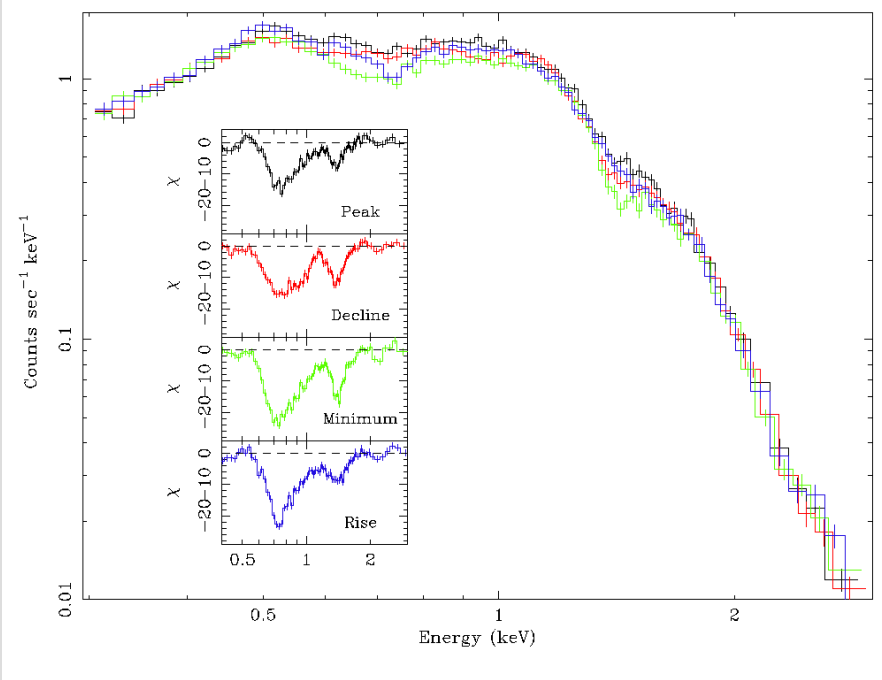


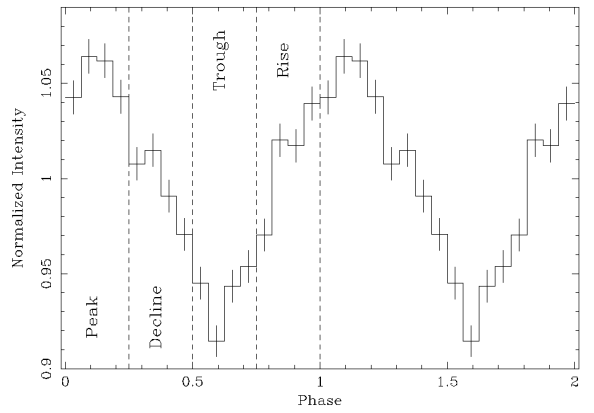
XMM-Newton RGS
Chandra LETGS
XMM-Newton EPIC-pn

provided by J. Vink

The case of 1E 1207.4-5209: X-ray spectrum



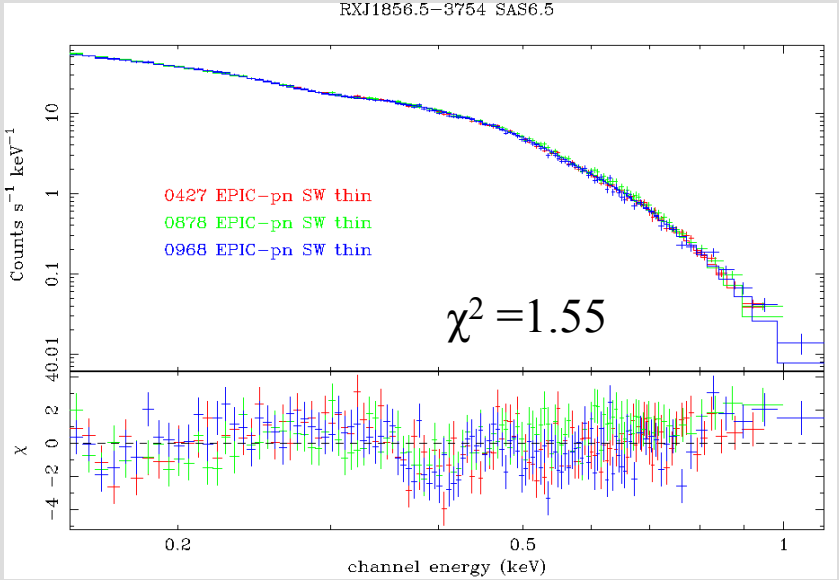


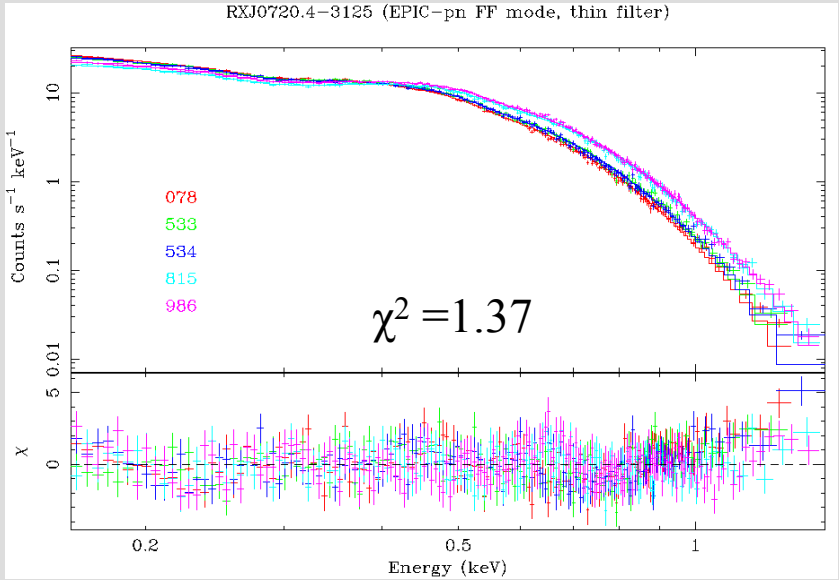


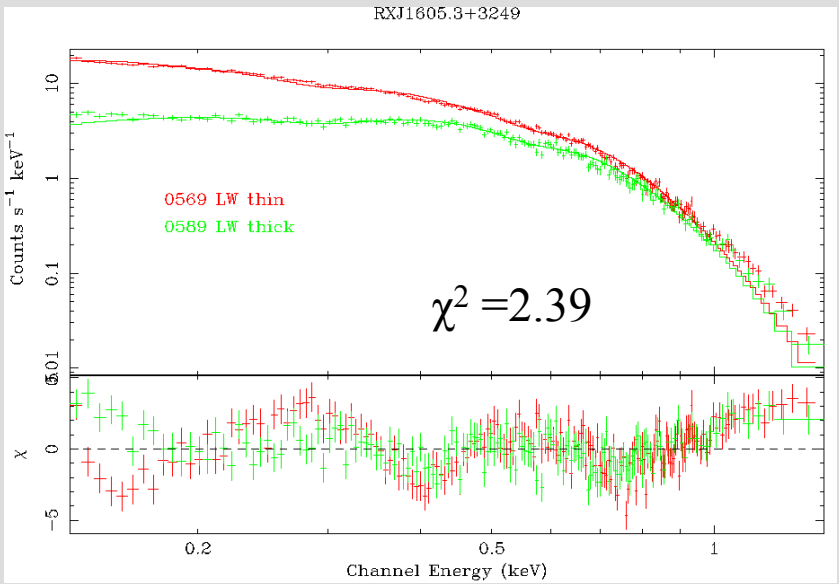
Absorption lines @
0.68 keV, 1.36 keV, 2.14 keV? and 2.83 keV?

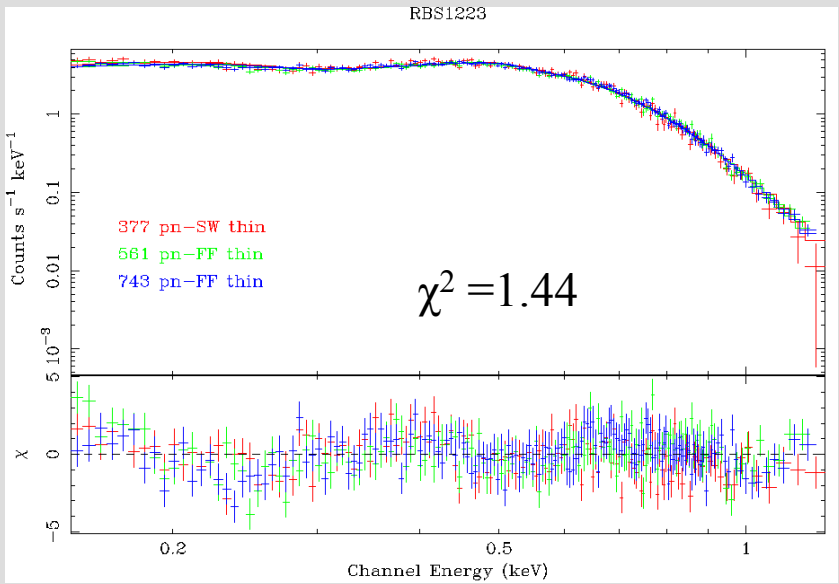
Bignami et al. (2003)

Multiple lines ?

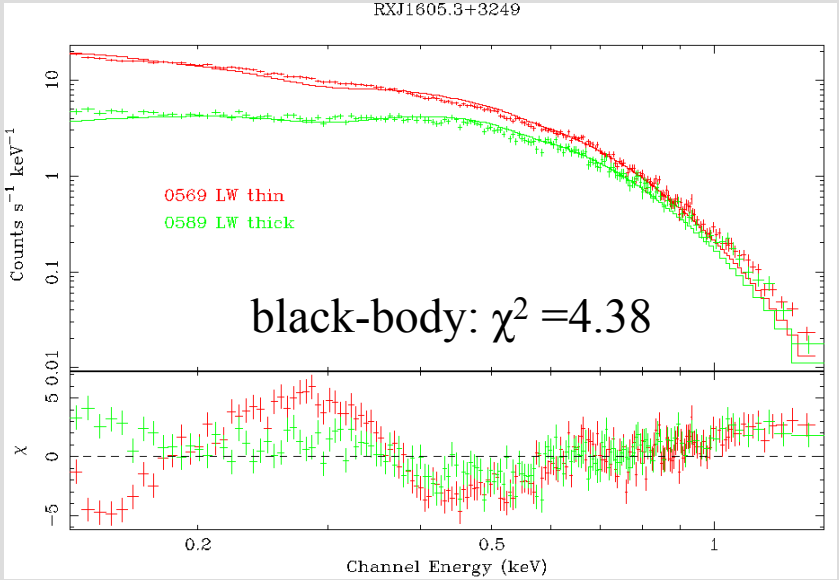


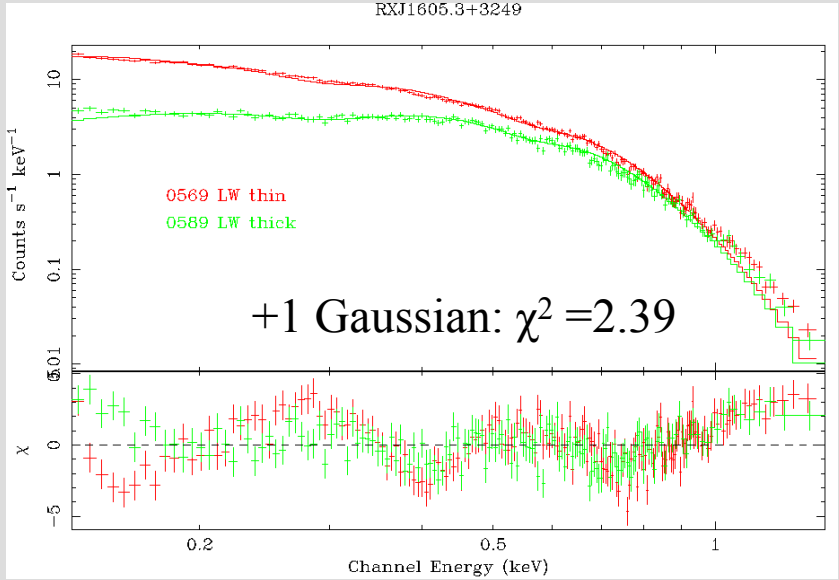


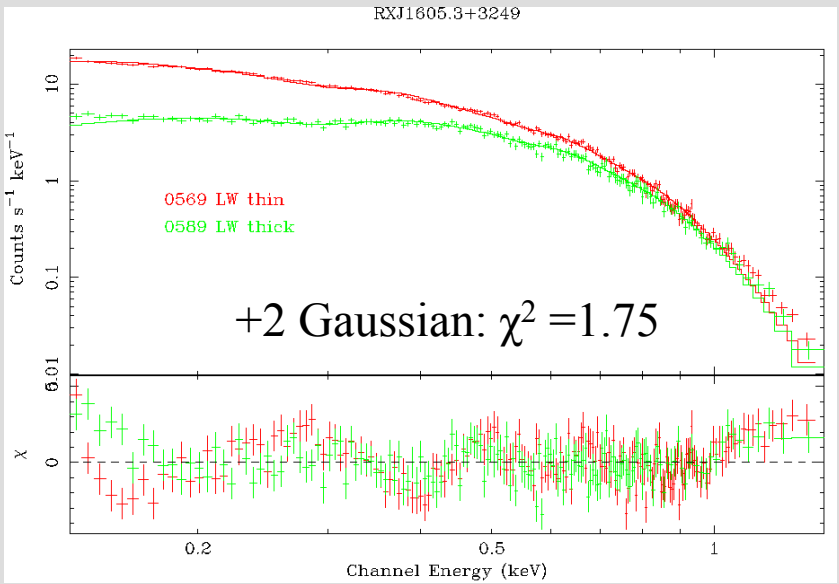


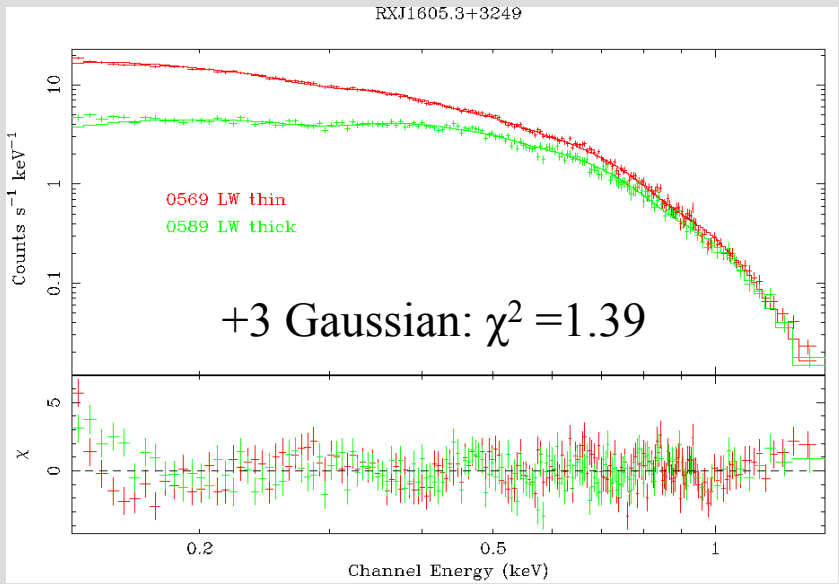


RX J1605.3+3249: Multiple lines ?









RX J1605.3+3249: Three absorption lines !

Line energies:

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

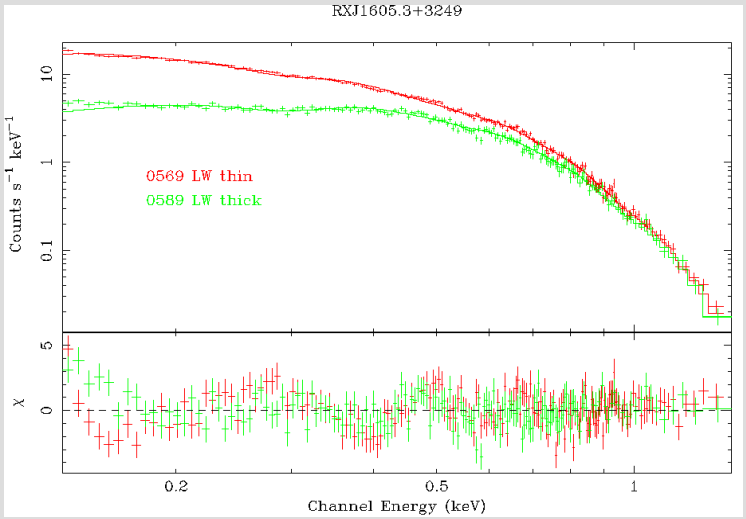
$E_1 : E_2 : E_3 = 2 : 3 : 4$

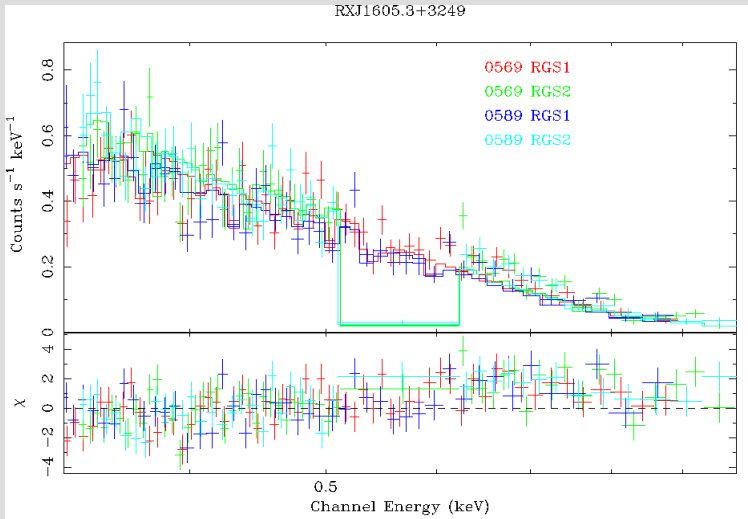
Absorbed line fluxes:

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

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

$EQW_1 = 96$ eV
$EQW_2 = 76$ eV
$EQW_3 = 67$ eV

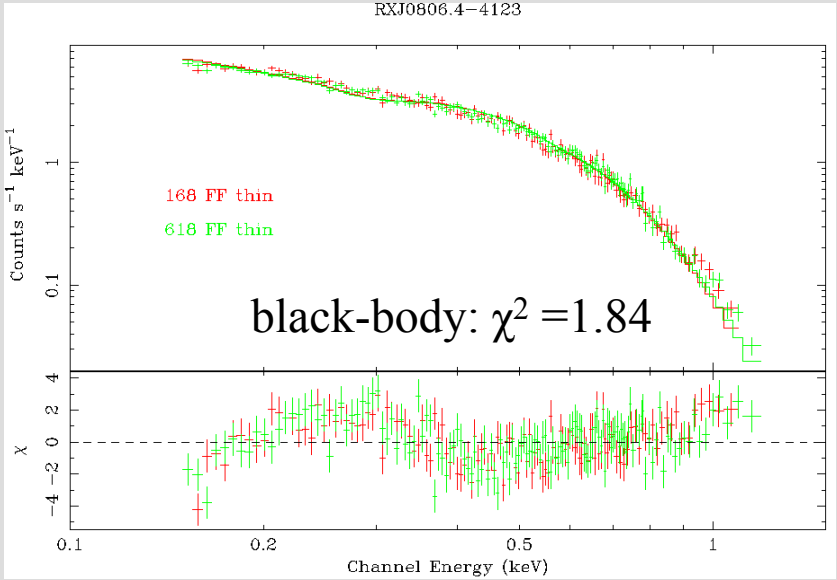


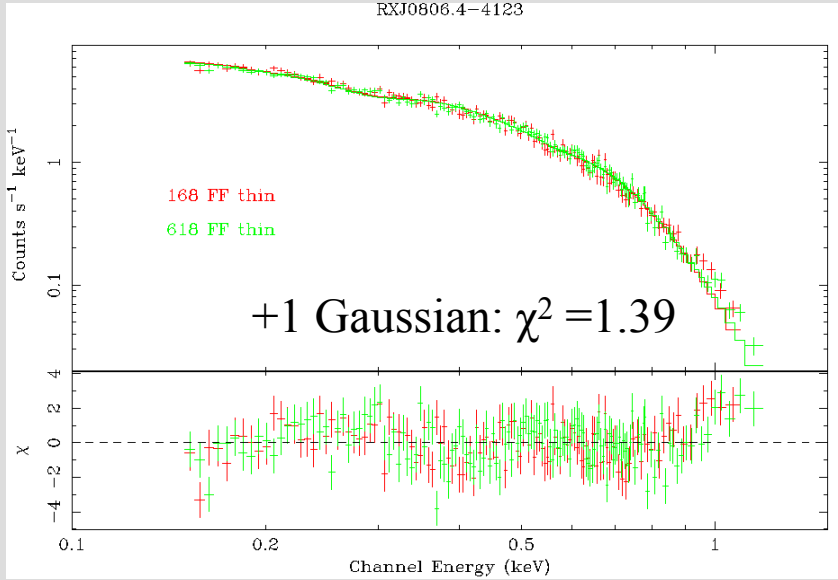


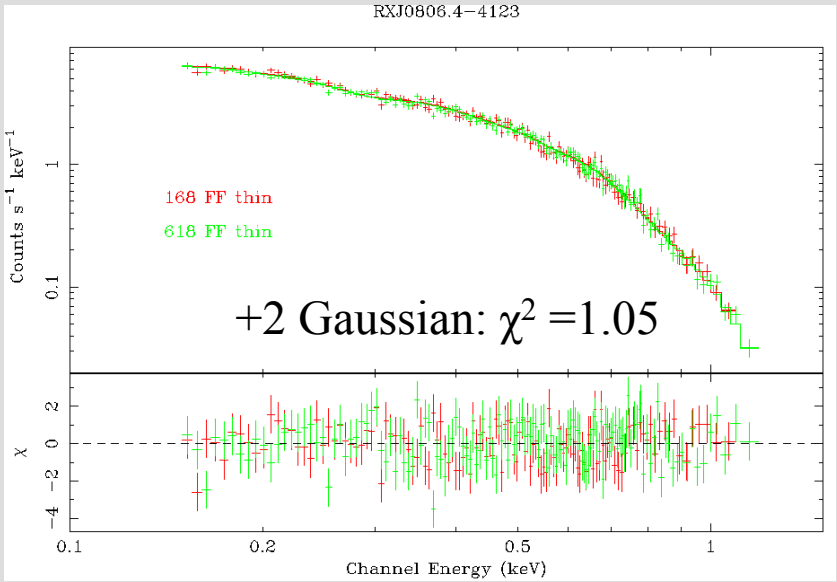
Harmonic lines: fundamental line at 200 eV ?
Caused by protons or electrons ?

Atomic line transitions ?
Hydrogen ruled out?

More harmonic lines ?







One line:

E_1 = 433 ± 16 eV

σ_1 = 100 eV fixed

Two lines:

E_1 = 306 ± 3 eV E_2 = 612 eV (linked to E_1)

$\sigma_1 = \sigma_2$ = 139 ± 6 eV

N_1/N_2 = 16.6

Summary, Magnetic fields

- 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)	308	2.4	6.2
RX J0806.4–4123	11.37	6%	< 18	430/306	< 14	8.6/6.1
1RXS J130848.6+212708	10.31	18%	< 9	302	< 10	6.0
RX J1605.3+3249				200		3.2
RX J1856.5–3754					~1	
1RXS J214303.7+212708	9.43	4%		~700		~14

Which lines are fundamental ?
Is RX J1605.3+3249 still consistent with cyclotron absorption by protons ?
Atomic line transitions ?
Pure dipole fields (RBS 1223) ?
Long spin periods + age of 10^6 years (cooling and dP/dt) require high B