

The Magnificent Seven: Nearby, Thermally Emitting, Isolated Neutron Stars

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A legacy of ROSAT

Proper motions and distances

Observations with XMM-Newton and Chandra

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

Ages, cooling of neutron stars

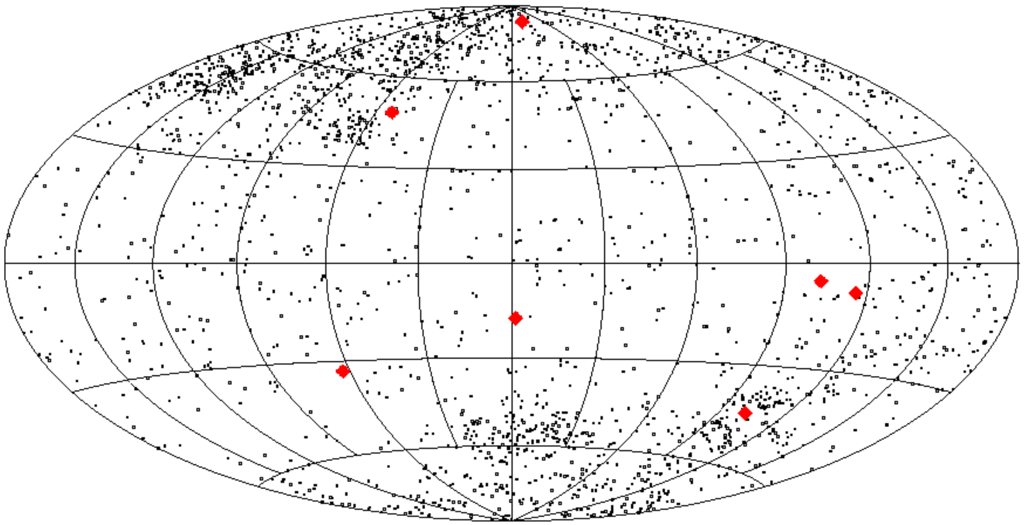
The case of RX J0720.4-3125

- **Spectral and temporal variations on long-term time scales**

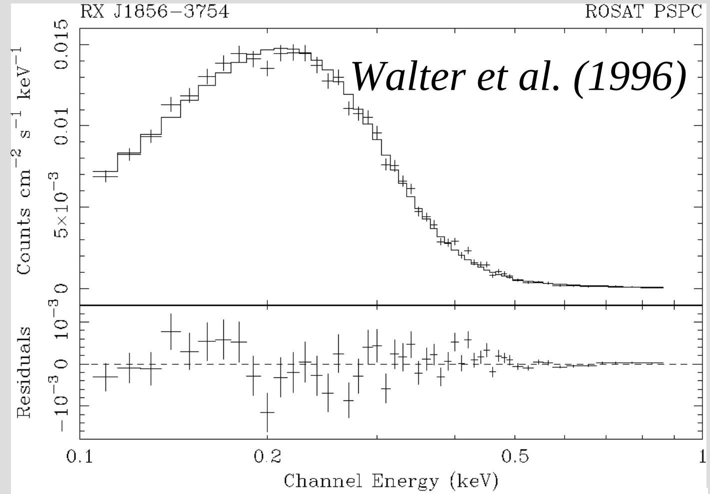
The Fast and the Furious:
Energetic Phenomena in Isolated Neutron Stars, Pulsar Wind Nebulae and Supernova Remnants
ESAC, Madrid, Spain, 22-24 May 2013

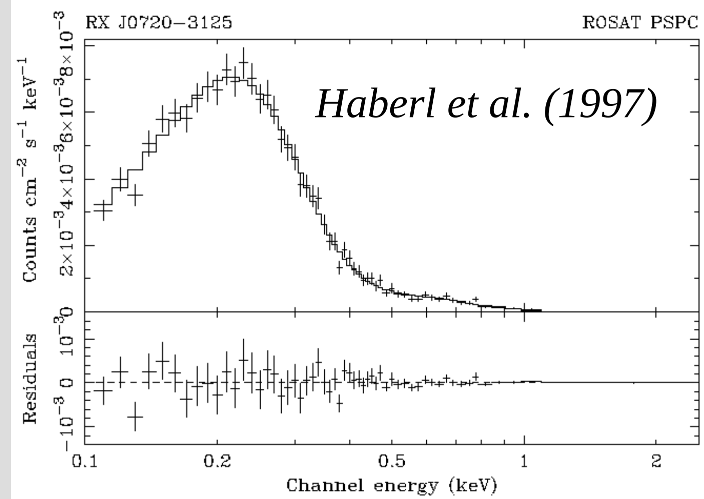
A Legacy of ROSAT: The discovery of seven radio-quiet neutron stars

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



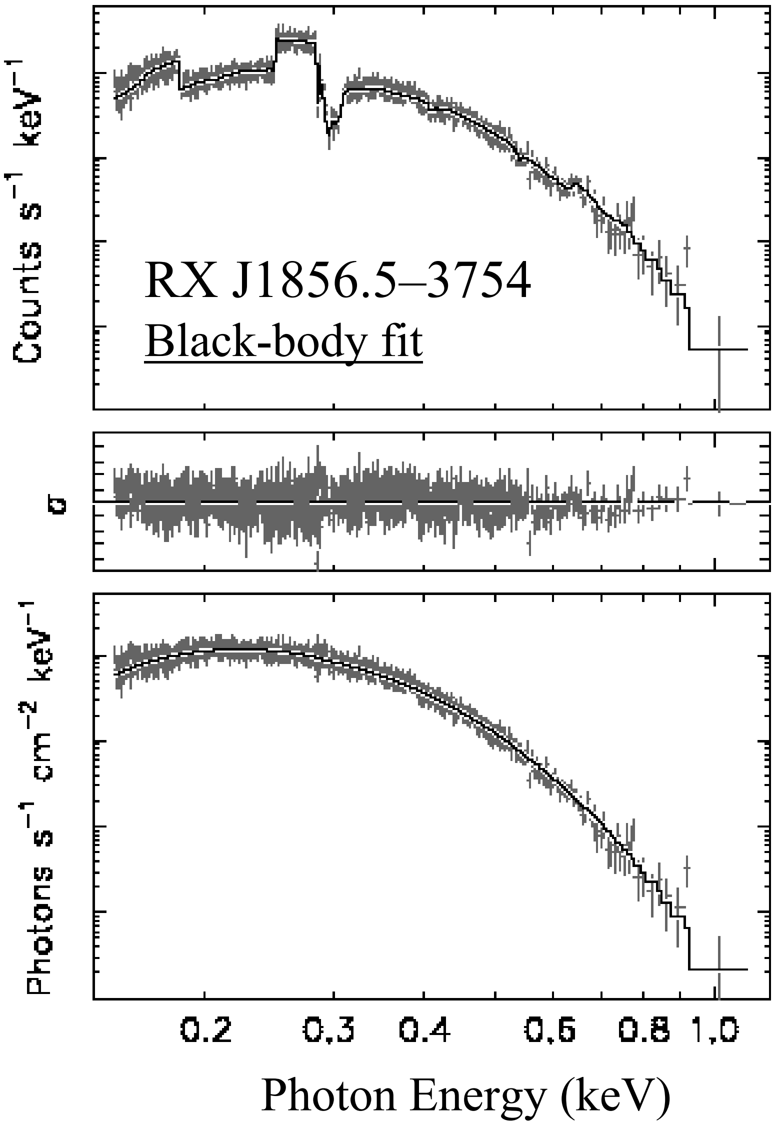


Blackbody-like X-ray spectra without non-thermal component!

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

The X-ray spectrum of RX J1856.5–3754

Chandra LETGS



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

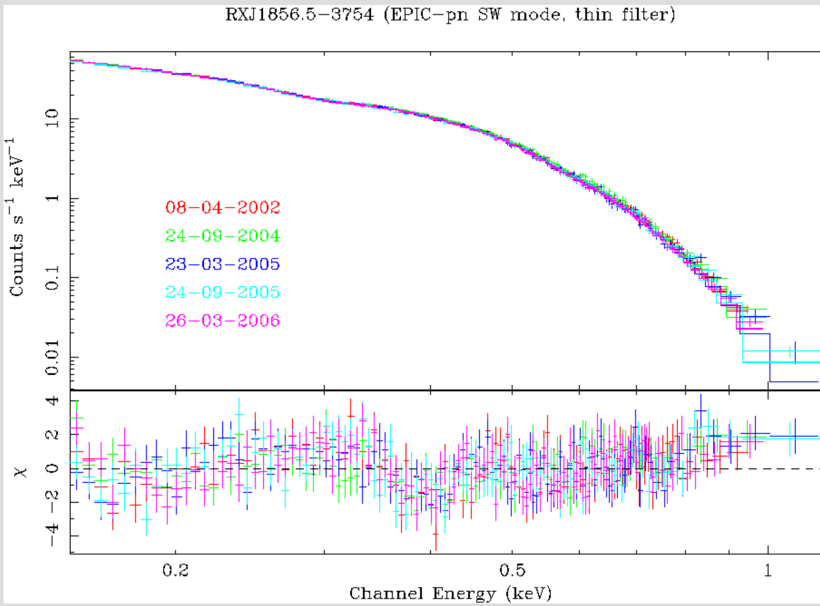
$kT_\infty = 63.5 \pm 0.2$ eV

$R_\infty = 5.5 \pm 0.15$ km (123pc)

$L_{bol} = 4.3 \cdot 10^{31}$ erg s^{-1}

No narrow absorption features !

Burwitz et al. (2003,2004)



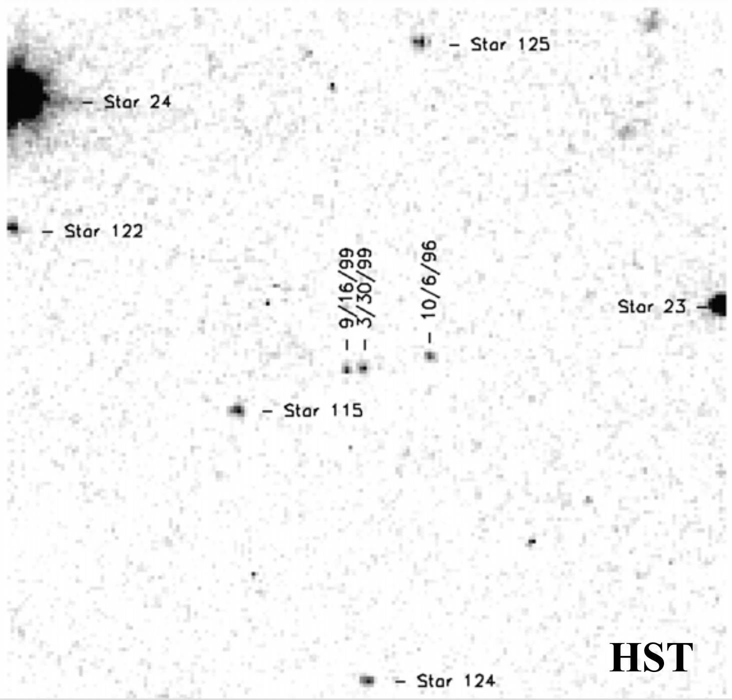
XMM EPIC-pn

Spectrum constant over time scales of years

Haberl (2006)

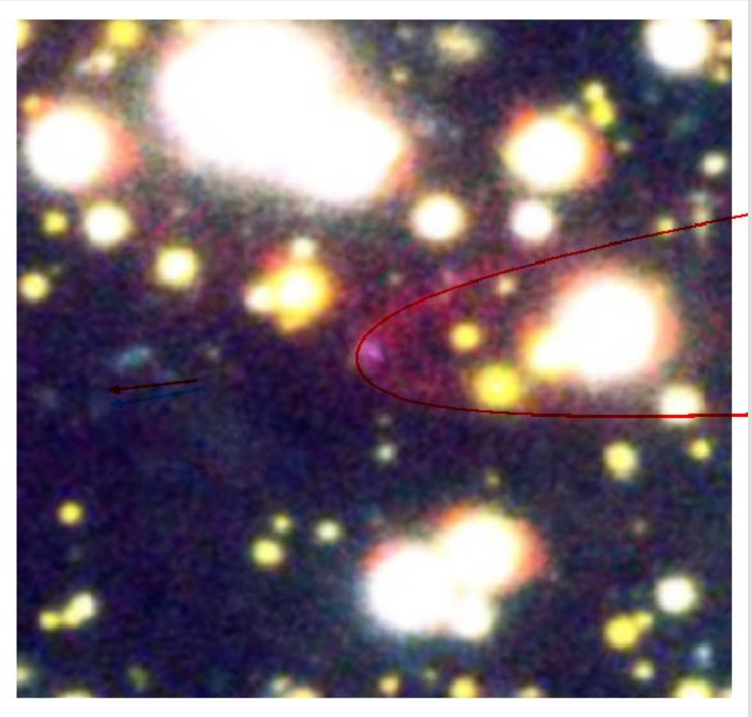
Proper motions, distances and velocities

RX J1856.5-3754



B = 25.2
Proper motion = 330 mas y^{-1}
Parallax 8.16 +0.9/-0.8 mas (1σ)
Distance = 123 +11/–15 pc
Tangential space velocity = 254 km s^{-1}
Kinematic age from back tracing to possible birth place ≈ $5 \cdot 10^5$ y

Walter et al. 2010
see also Walter 2001, Kaplan et al. (2002), Walter & Lattimer 2002, van Kerkwijk & Kaplan (2007)



Bowshock Nebula **VLT**

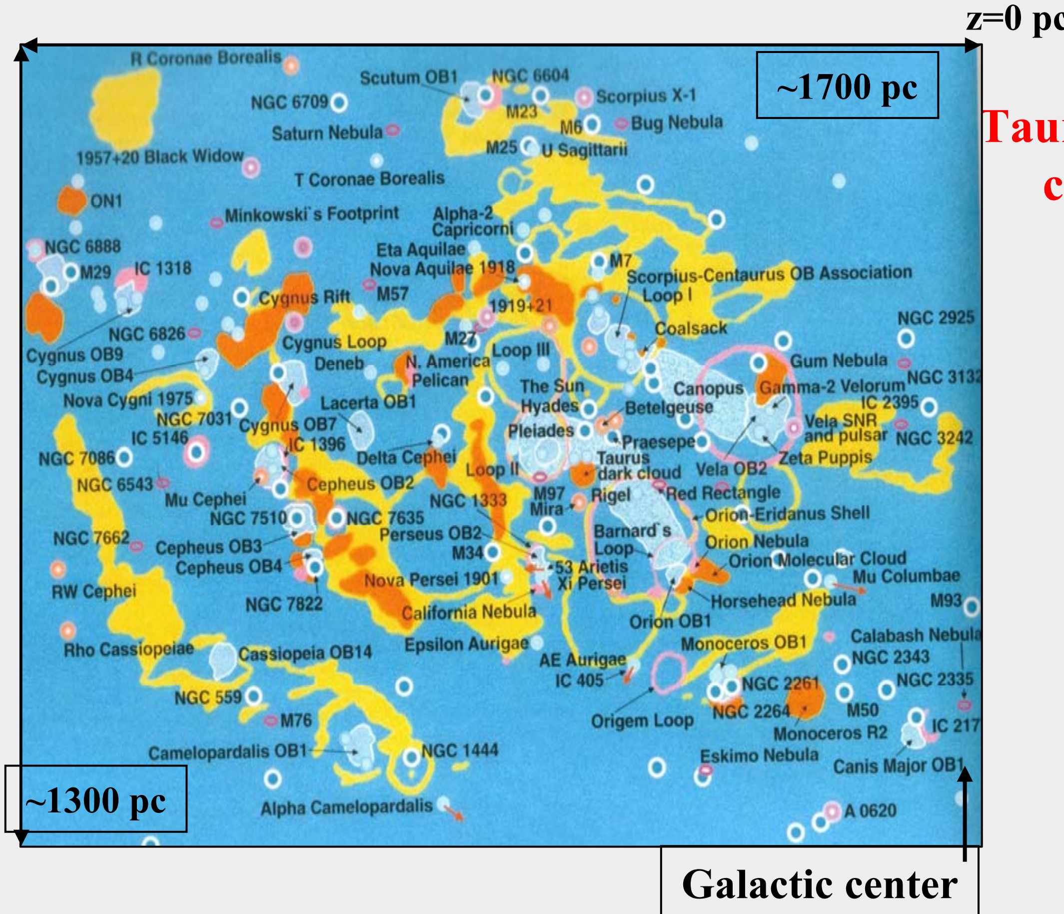
Kerkwijk & Kulkarni (2001)

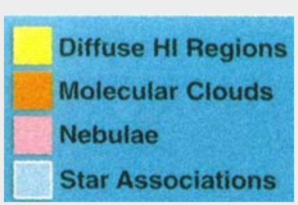
Powered by magnetic dipole braking:
$dE/dt = 4.5 \cdot 10^{32}$ erg s^{-1}, $t = 5 \cdot 10^5$ y
$B \approx 10^{13}$ G

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

The inhomogenous Interstellar Medium (B. Posselt)

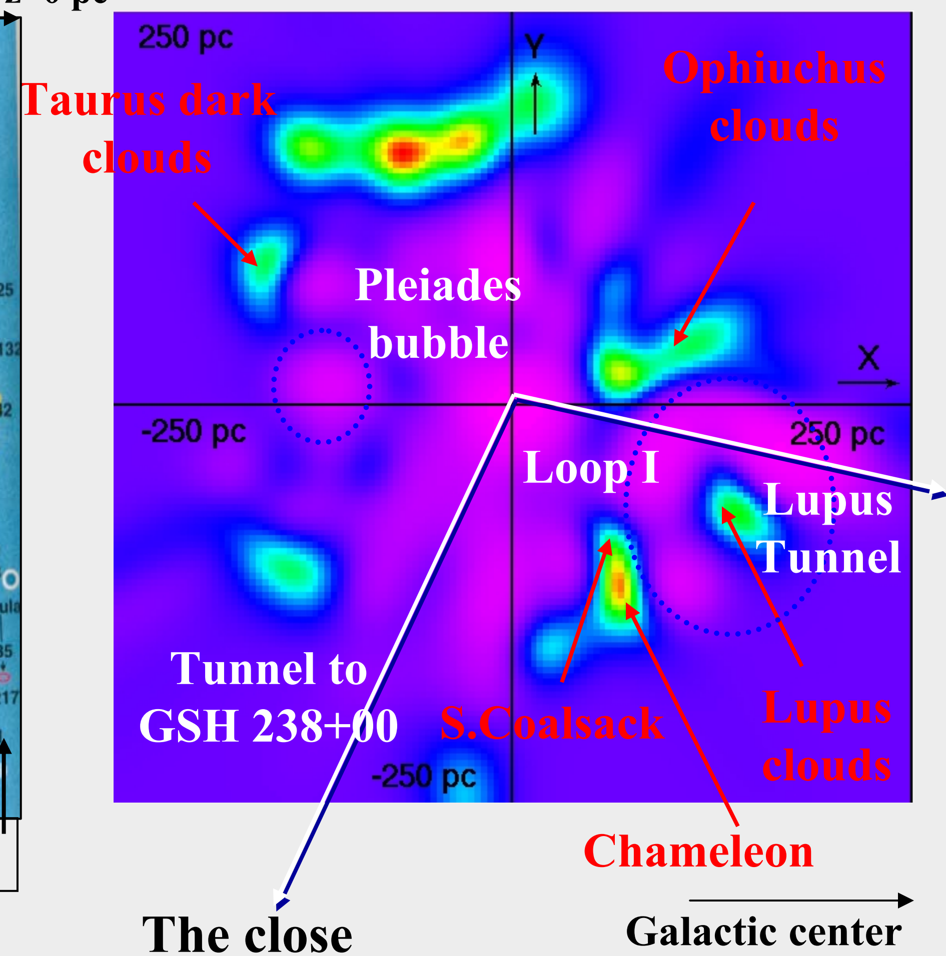
Henbest & Couper 1994





Within one kpc around the sun

Lallement et al. 2003 (NaI D-line)
Breitschwerdt et al. 2005



The close solar neighbourhood

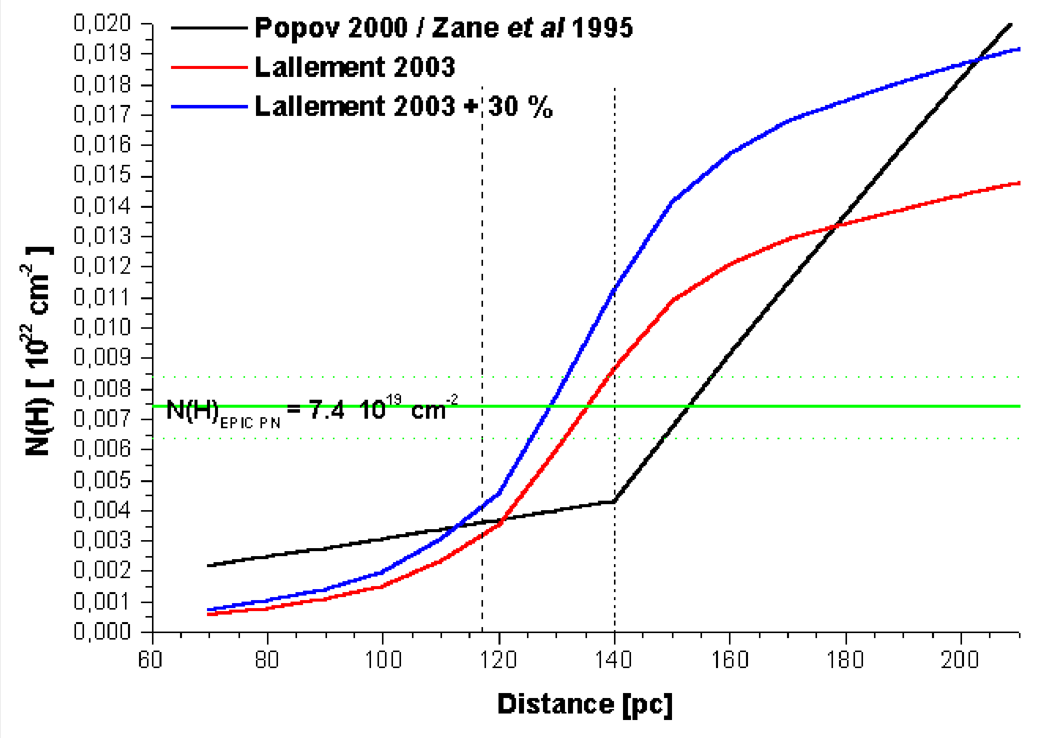
Distance estimates from X-ray absorption

In the direction of RX J1856.5-3754

(l = 359°, b = –17°)

Walter et al. 2010: 123 +11/–15 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)	>400
RX J1605.3+3249	2.0 (3L)	320–400
RBS 1774	2.4 (1L)	380–440

Posselt et al. 2007, Ap&SS 308, 171

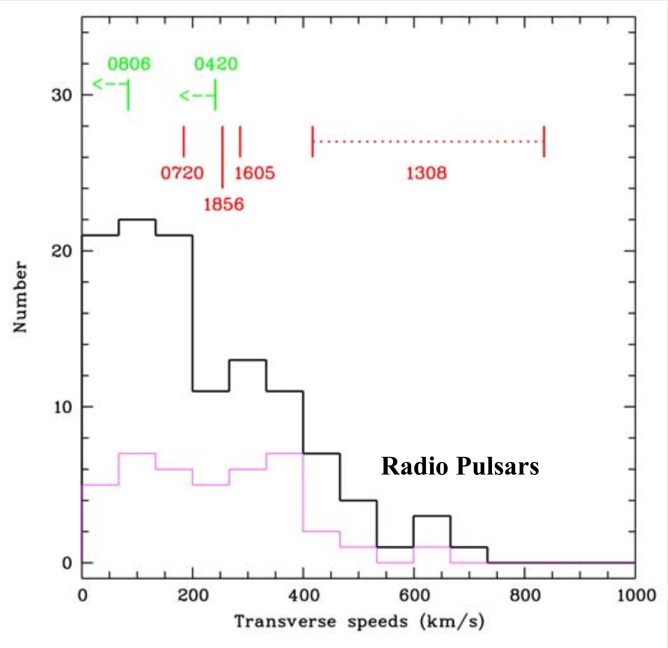
Proper motions, distances and velocities

Object	μ mas y^{-1}	distance pc	v_T km s^{-1}
RX J0420.0–5022	<123[2]	(300–370)[1]	<200
RX J0720.4–3125	108±1	360 +172/-88	184
		280 +210/-85	143[4]
RX J0806.4–4123	<86[2]	(210–275)[1]	<96
RX J1308.8+2127	220±25[2]	(400-800)[1]	417-835
RX J1605.3+3249	155±3	(300–415)[1]	286
RX J1856.5–3754	331±2	123 +11/-15[3]	193
RX J2143.0+0654		(365–455)[1]	

[1]constraints from absorption
[2]X-ray measurements (Chandra)

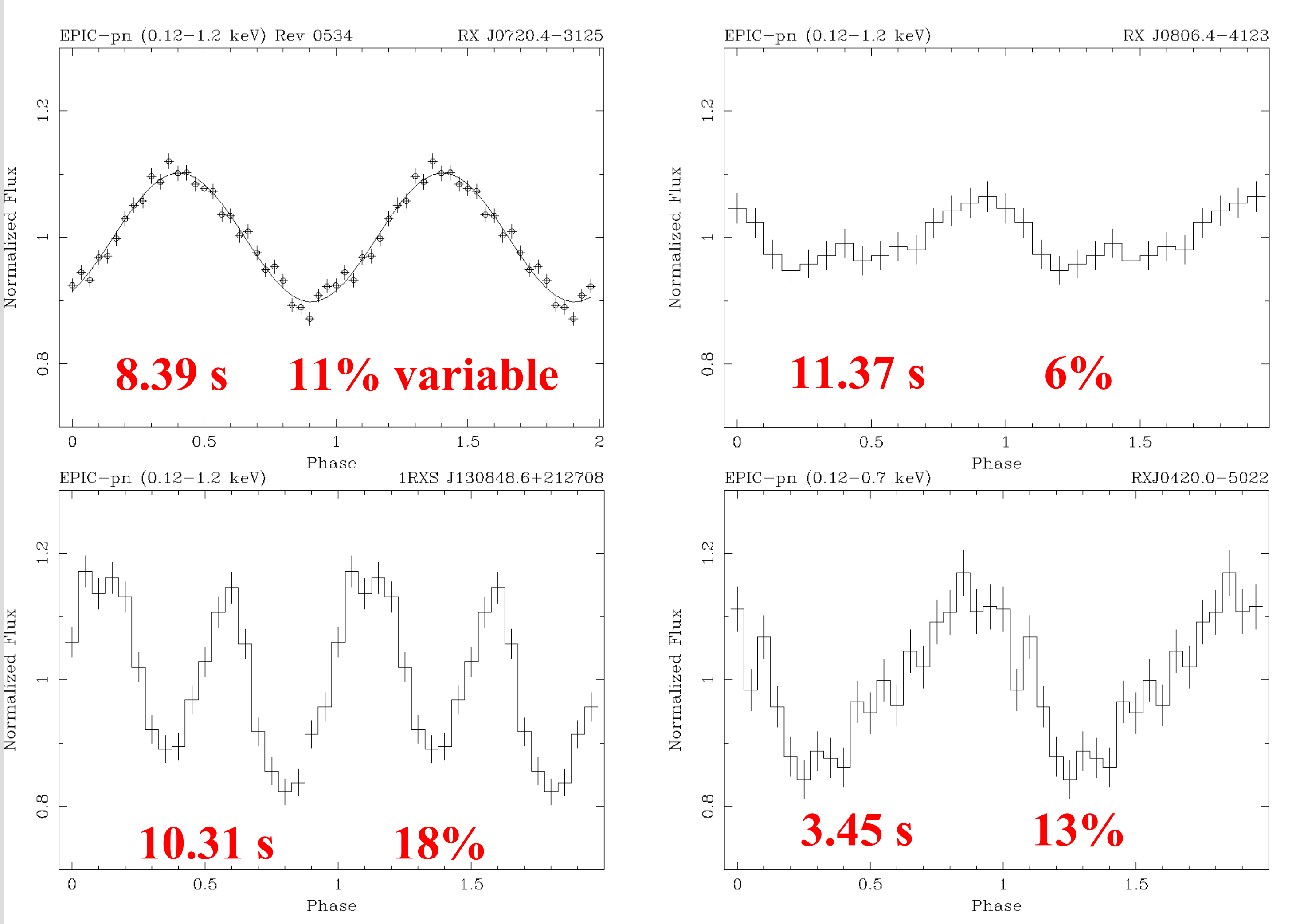
Motch et al. 2009 (A&A 497, 423)

[3]from Walter et al. 2010
[4]from Eissenbeiß 2011 (PhD thesis)



High transverse speeds:
No significant heating due to accretion from ISM !!

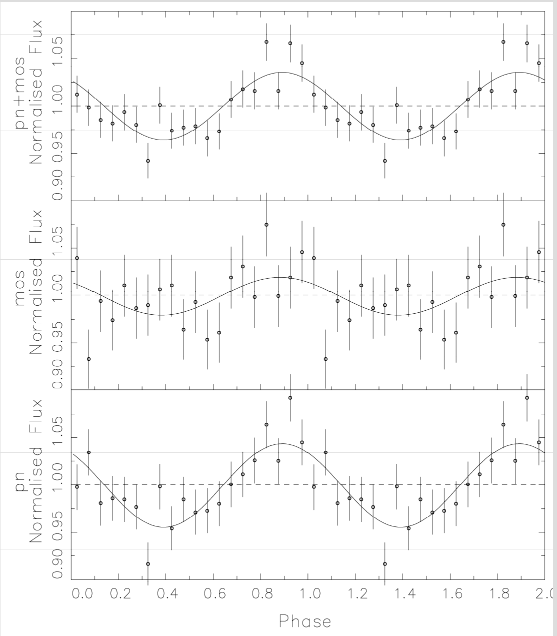
X-ray pulsations

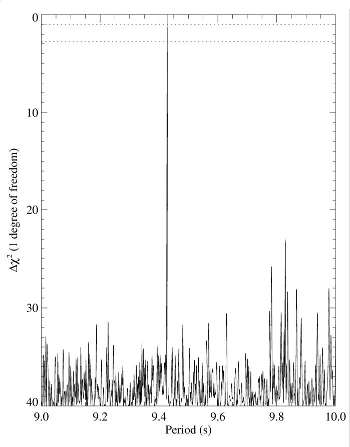


Non-uniform temperature distribution on neutron star surface

X-ray pulsations

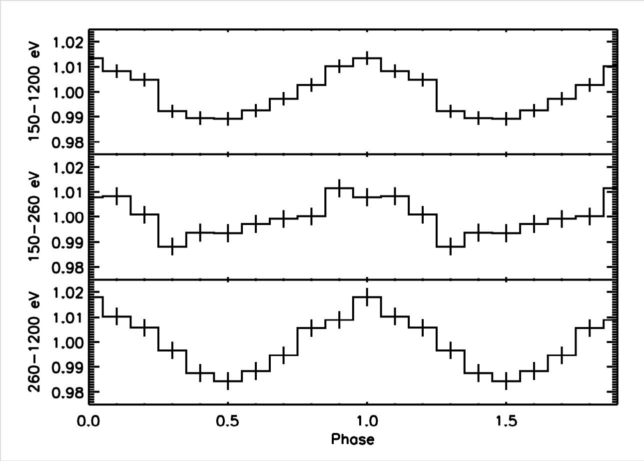
RX J2143.0+0654





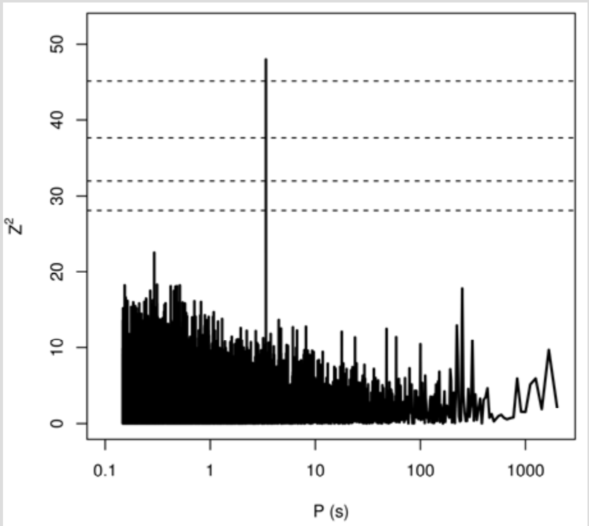
P = 9.437 s
pulsed fraction ~4%
Zane et al. 2005

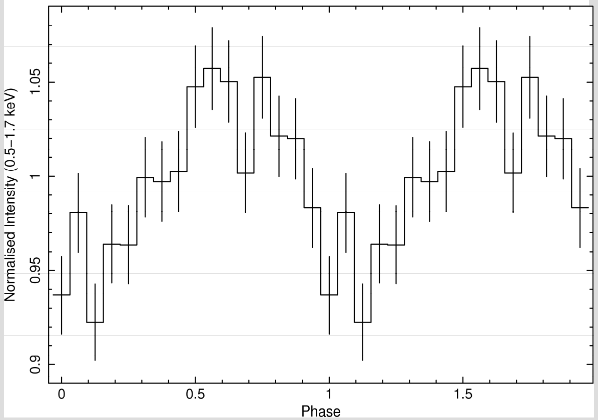
RX J1856.5-3754



P = 7.055 s
pulsed fraction ~1.2%
Tiengo & Mereghetti 2007

RX J1605.3+3249

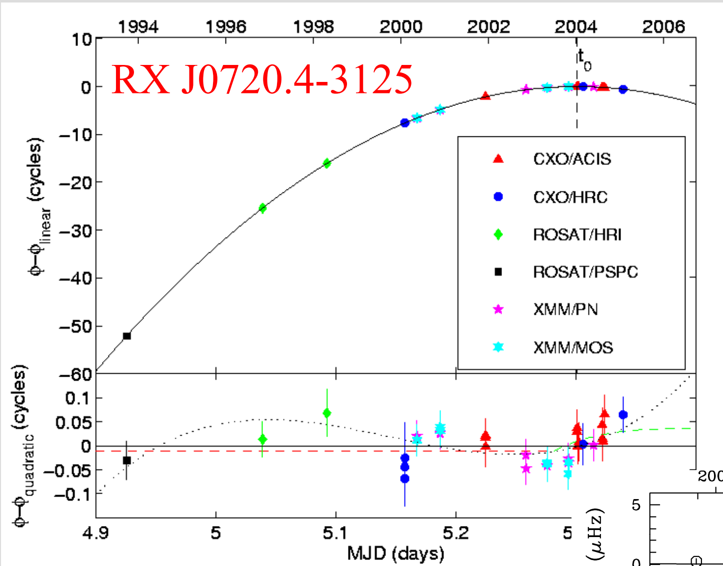




P = 3.388 s
PF ~5% (0.5-1.7 keV)
Pires et al. in prep.

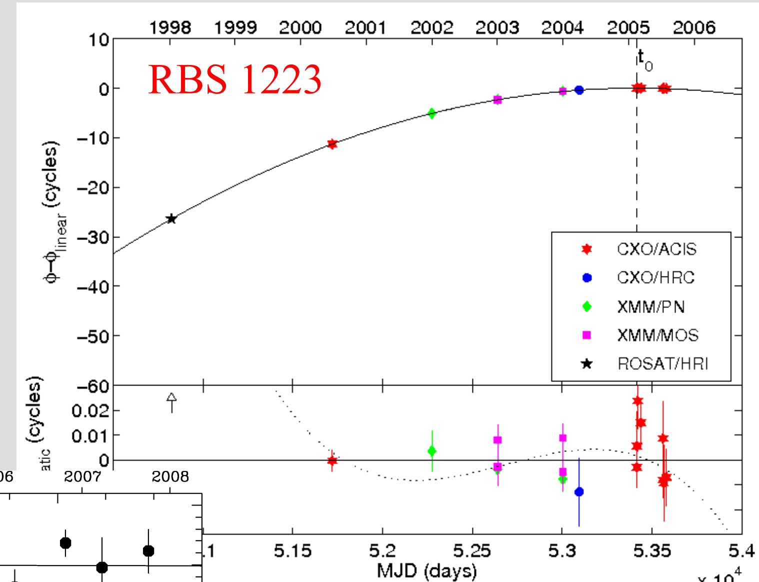
The M7 are pulsars with periods 3.39 – 11.37 s

Spin Period Evolution

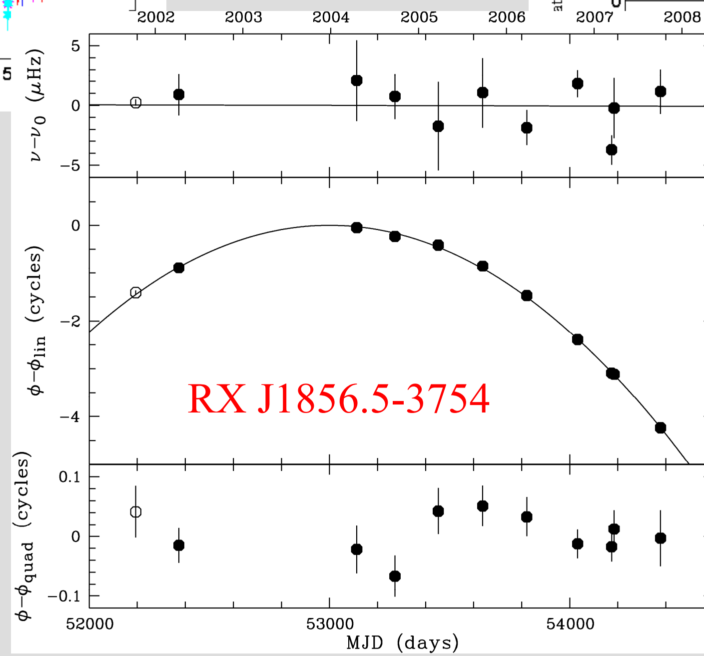


Kaplan & van Kerkwijk 2005a

Models for constant dP/dt

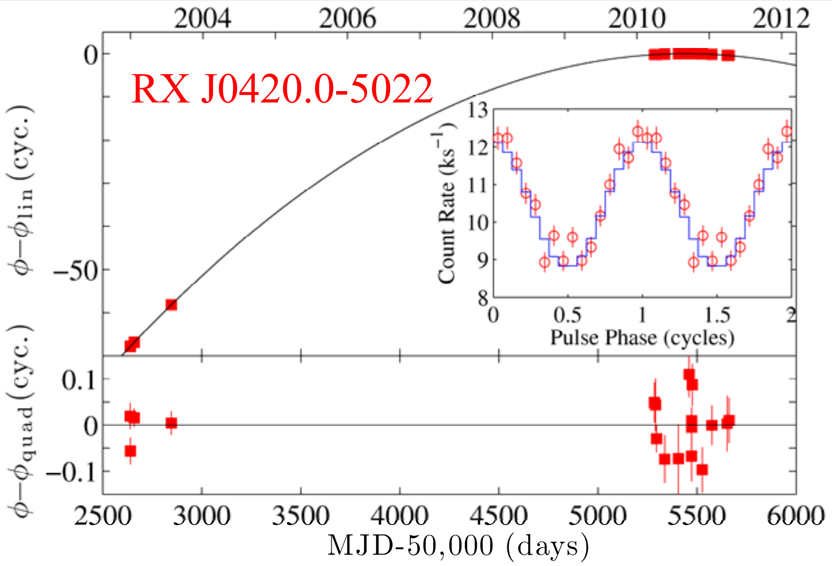


Kaplan & van Kerkwijk 2005b

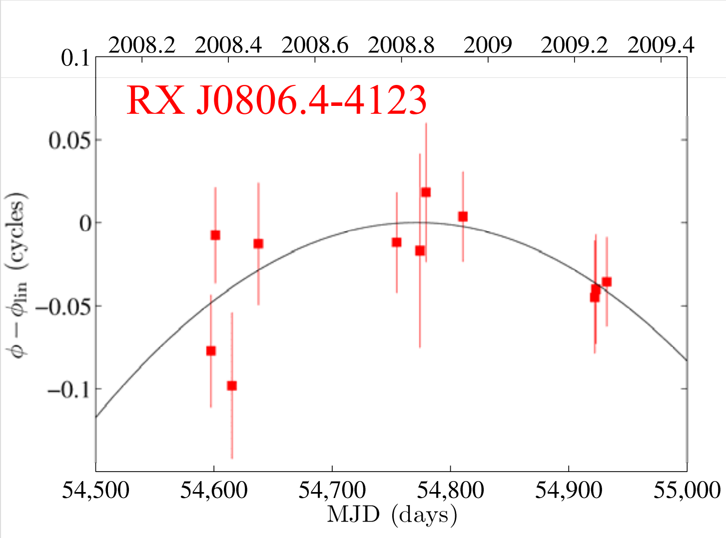


van Kerkwijk & Kaplan 2008

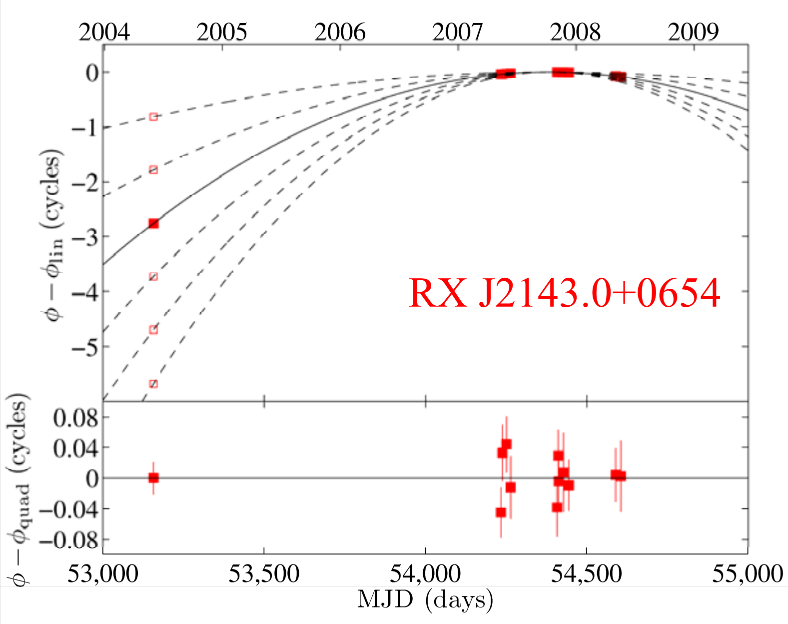
Spin Period Evolution



Kaplan & van Kerkwijk 2011



Kaplan & van Kerkwijk 2009b



Kaplan & van Kerkwijk 2009a

Magnetic fields

Magnetic dipole braking → $B_{dip} = 3.2 \cdot 10^{19} (P \cdot dP/dt)^{1/2}$

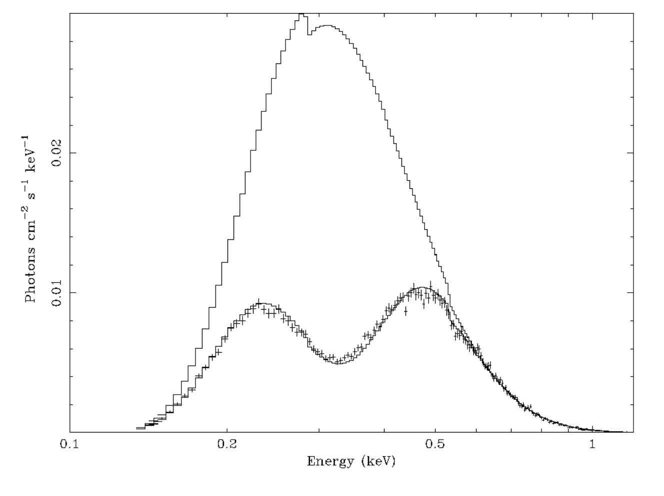
$\tau_{char} = P/2(dP/dt)$

Object	P [s]	dP/dt [10^{-13} ss^{-1}]	τ_{char} [Myr]	B_{dip} [10^{13} G]	Ref.	Kinematic Age [Myr]
RX J0420.0–5022	3.45	0.28(3)	2.0	1.0	1	
RX J0720.4–3125	8.39	0.698(2)	1.9	2.4	2	0.85
RX J0806.4–4123	11.37	0.55(30)	3.3	2.5	3	
1RXS J1308.8+2127	10.31	1.120(3)	1.5	3.4	4	
RX J1605.3+3249	3.39					
RX J1856.5–3754	7.06	0.297(7)	3.8	1.5	5	0.46
1RXS J2143.0+0654	9.43	0.4(2)	3.7	2.0	6	

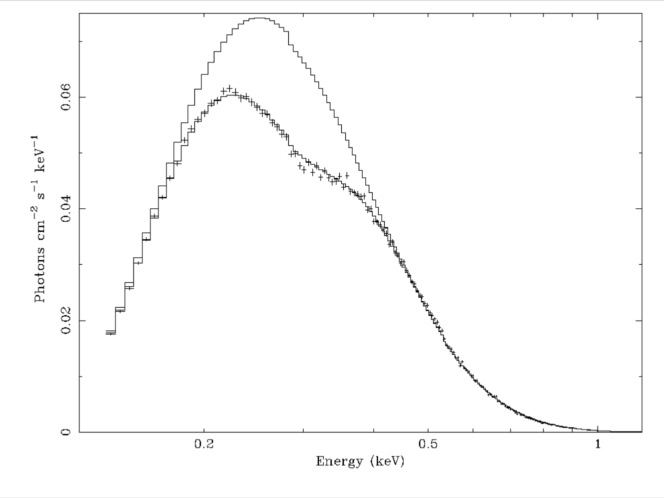
1 Kaplan & van Kerkwijk 2011, ApJ 740, L30
2 Kaplan & van Kerkwijk 2005a, ApJ 628, L45; van Kerkwijk et al. 2007, ApJ 659, L149
3 Kaplan & van Kerkwijk 2009b, ApJ 705, 798
4 Kaplan & van Kerkwijk 2005b, ApJ 635, L65
5 van Kerkwijk & Kaplan 2008, ApJ 673, L163
6 Kaplan & van Kerkwijk 2009a, ApJ 692, L62

XMM-Newton observations of the M7: absorption features

RBS 1223
EW = 150 eV
Pulse phase variations
Haberl et al. (2003)

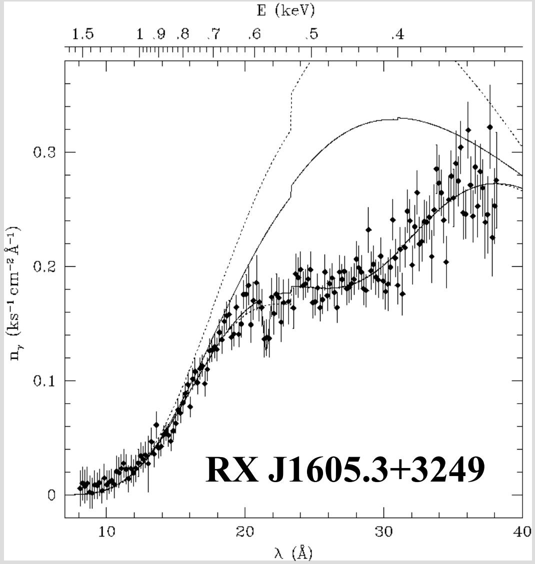


XMM-Newton EPIC-pn

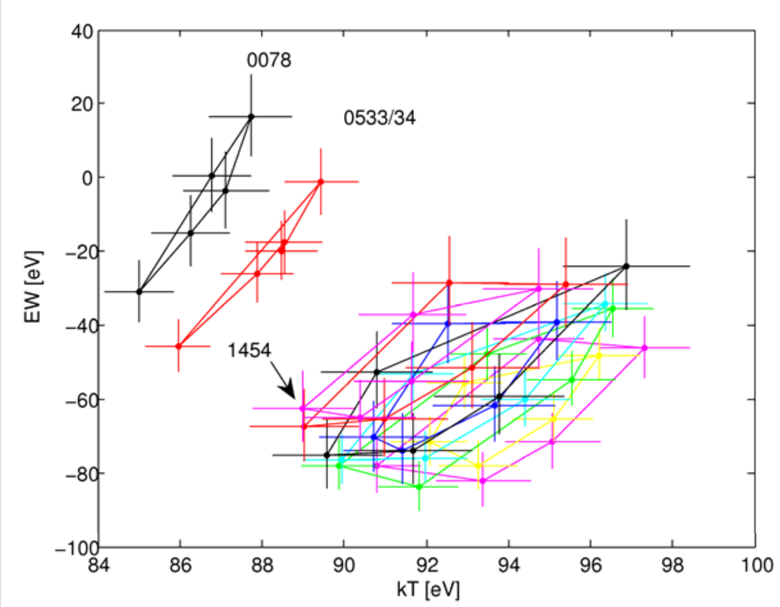


RX J0720.4–3125
variable with pulse phase and over years
Haberl et al. (2004), Hohle et al. (2012)

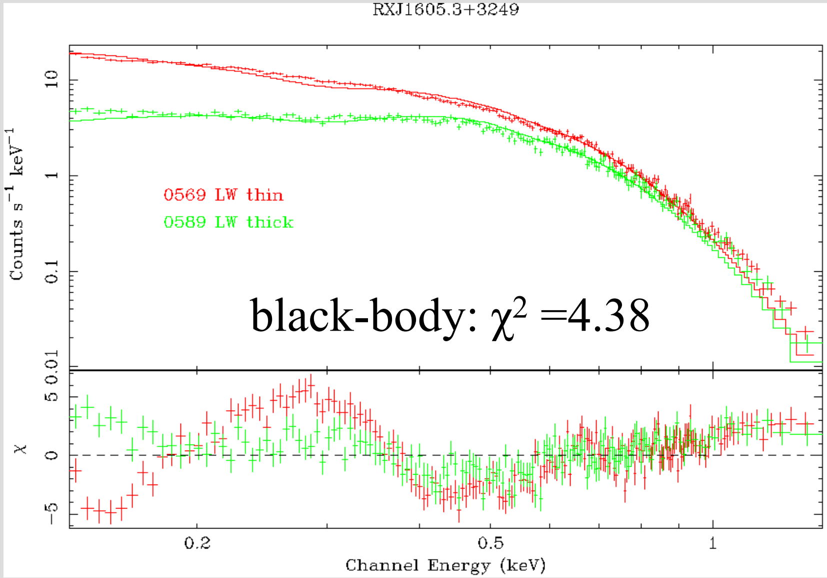
XMM-Newton RGS

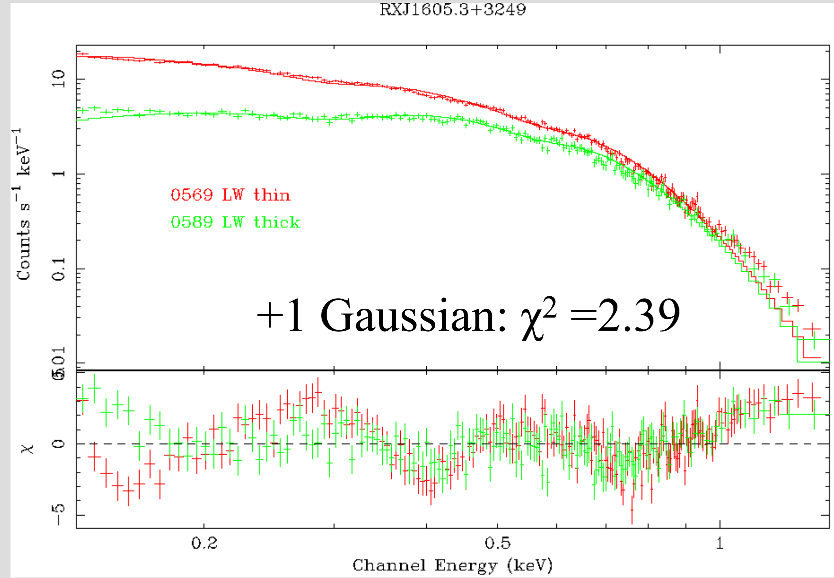


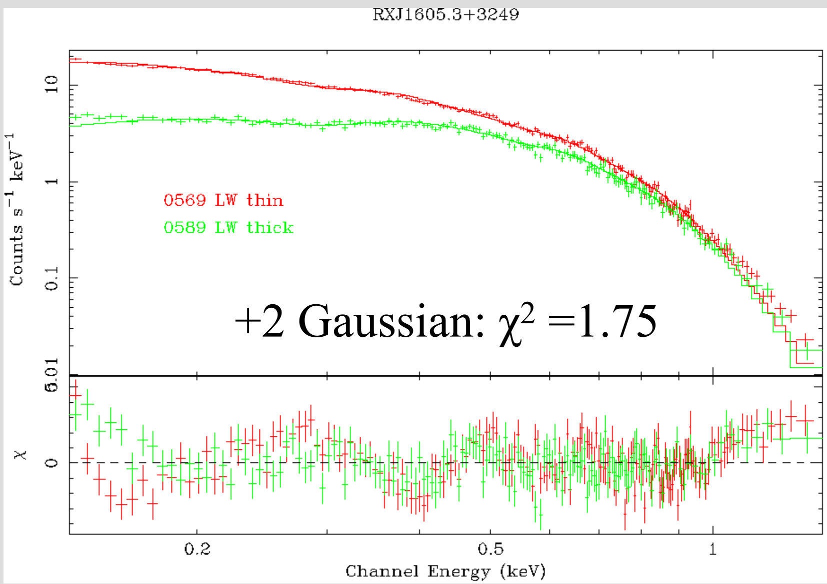
$kT = 95$ eV, $N_H = 0.8 \cdot 10^{20}$ cm^{-2}
$E_{line} = 450 – 480$ eV
Van Kerkwijk et al. (2004)
EPIC-pn: evidence for multiple lines

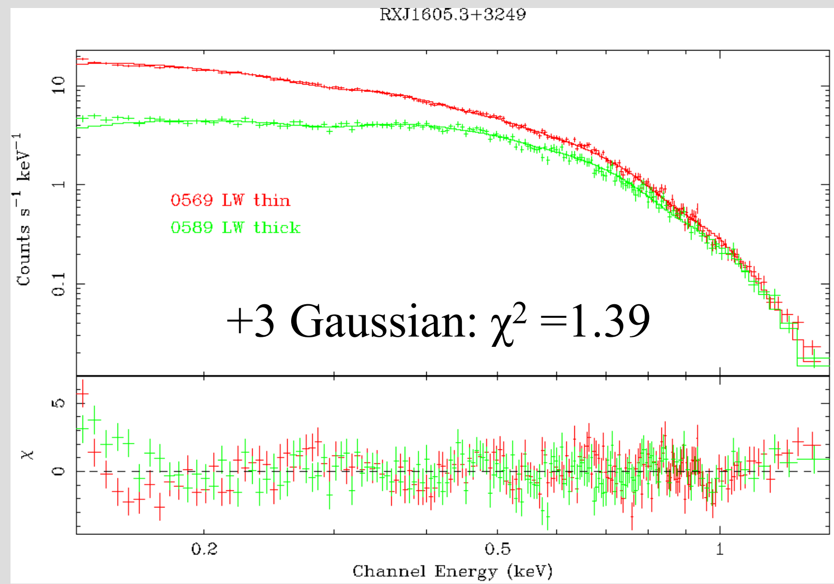


RX J1605.3+3249: Evidence for multiple lines









The origin of the absorption features

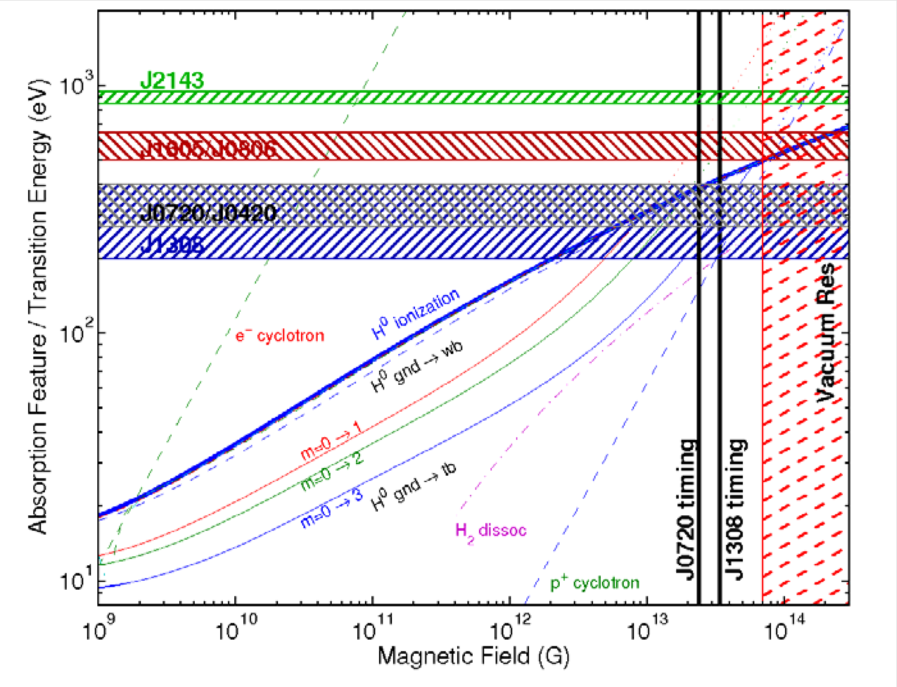
Proton cyclotron absorption line ?

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

Magnetic fields II

Unique opportunity to estimate B in two independent ways:

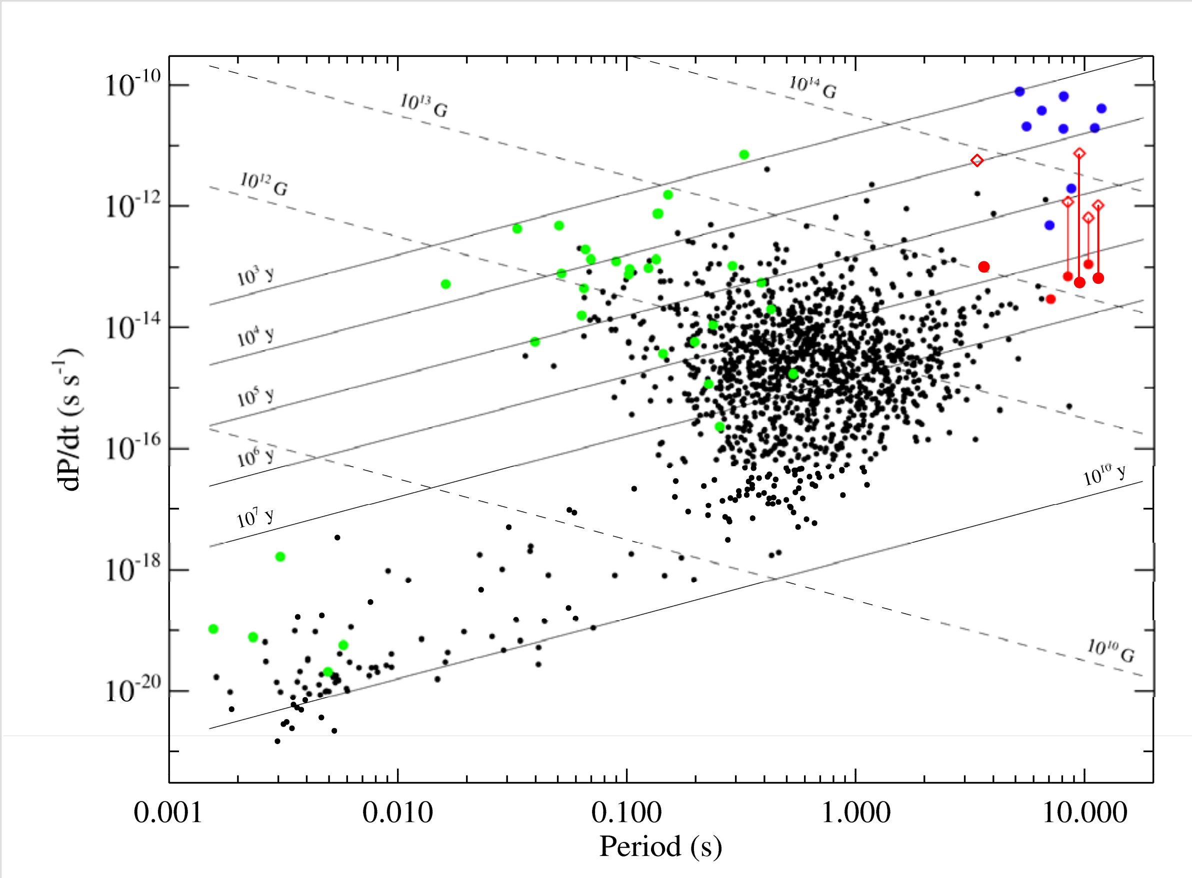
- Magnetic dipole braking (P, dP/dt)
- Proton cyclotron absorption → $B = 1.6 \cdot 10^{11}\, E(eV)/(1-2GM/c^2R)^{1/2}$

Object	P [s]	B_{dip} [10^{13} G]	E_{cyc} [eV]	B_{cyc} [10^{13} G]	B_{cyc}/B_{dip}
RX J0420.0–5022	3.45	1.0	?		
RX J0720.4–3125	8.39	2.4	280	5.6	2.3
RX J0806.4–4123	11.37	2.5	430/306 a)	8.6/6.1	2.4-3.4
1RXS J1308.8+2127	10.31	3.4	300/230 a)	6.0/4.6	1.4-1.8
RX J1605.3+3249	3.39		450/400 b)	9/8	
RX J1856.5–3754	7.06	1.5	–	–	
1RXS J2143.0+0654	9.43	2.0	750	15	7.5

a) Spectral fit with single line / two lines

b) With single line / three lines at 400 eV, 600 eV and 800 eV

Pulsars



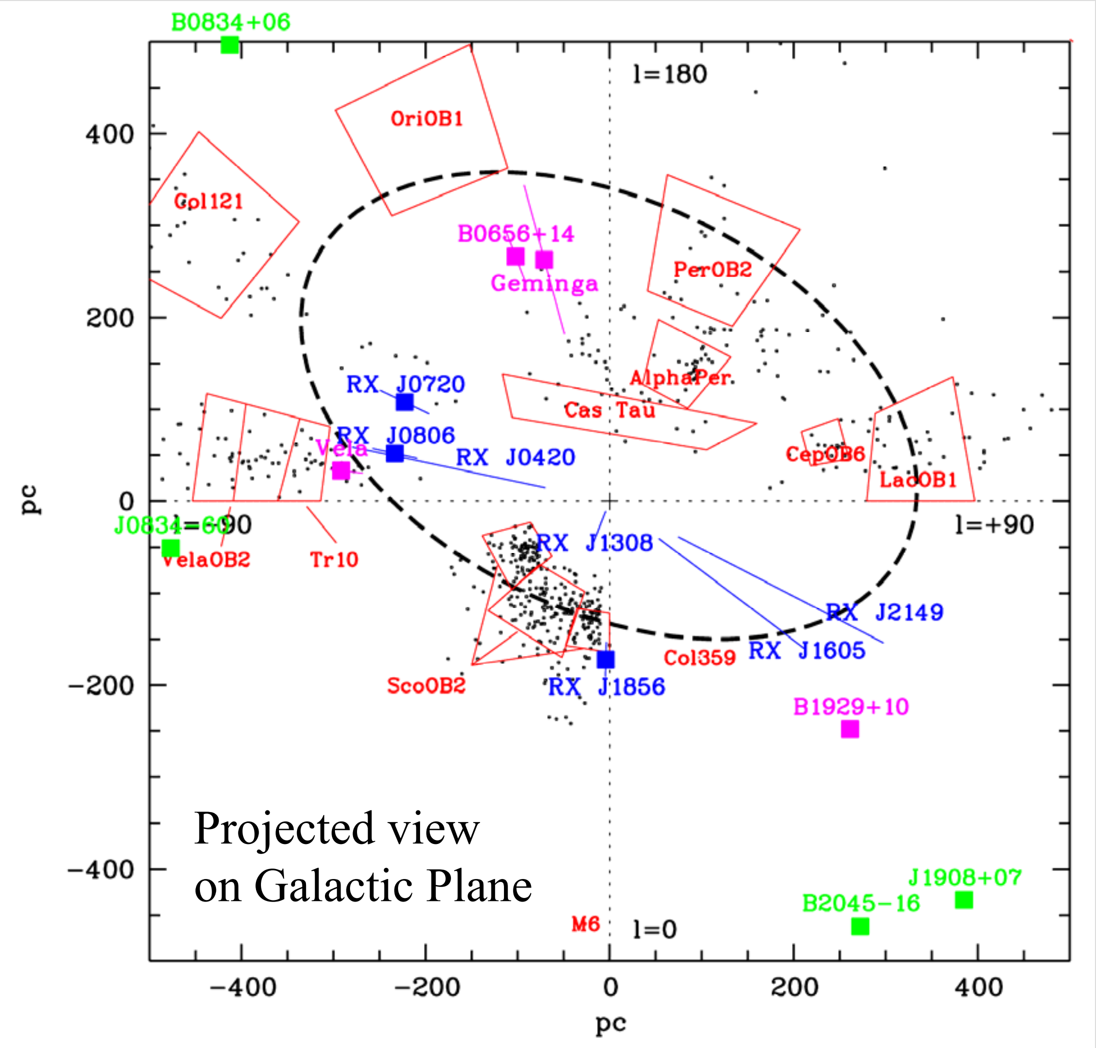
high-energy detections (incomplete)

AXPs / SGRs (magnetars)

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

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

Neutron star birth places – kinematic ages



Motch et al. 2007, Ap&SS 308, 217:

Blue lines indicate possible INS positions assuming distances (unless better known) between 100 and 400 pc.

Red boxes show positions of OB associations.

RXJ1856: Upper Sco OB2

RXJ0720: Tr 10 + Vela OB2

RXJ1605: Upper Sco OB2

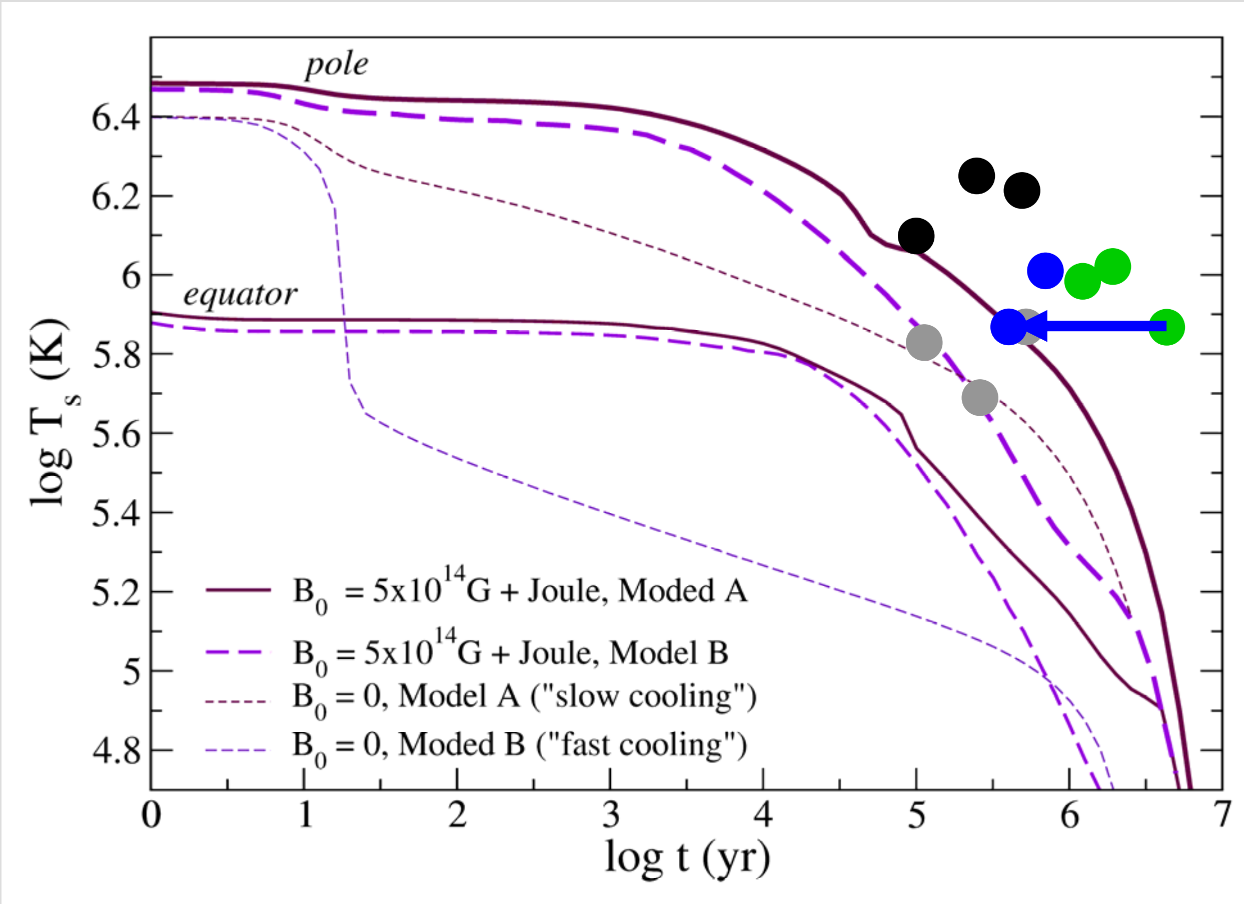
Tetzlaff et al. 2011:

RXJ1856: Upper Sco
0.46 ± 0.05 Myr

RXJ0720: Trumpler 10
0.85 ± 0.15 Myr
runaway star HIP 43158
→ current distance
286 +27/-23 pc

Cooling of magnetized neutron stars

Aguilera et al. 2008 (A&A 486, 255)



Spin-down age P/(2dP/dt)

Geminga

PSR B1055

PSR B0656

RX J0720

RBS 1223

RX J1856

RX J1856, RX J0720:
kinematic age shorter

Dipole braking model not suitable?

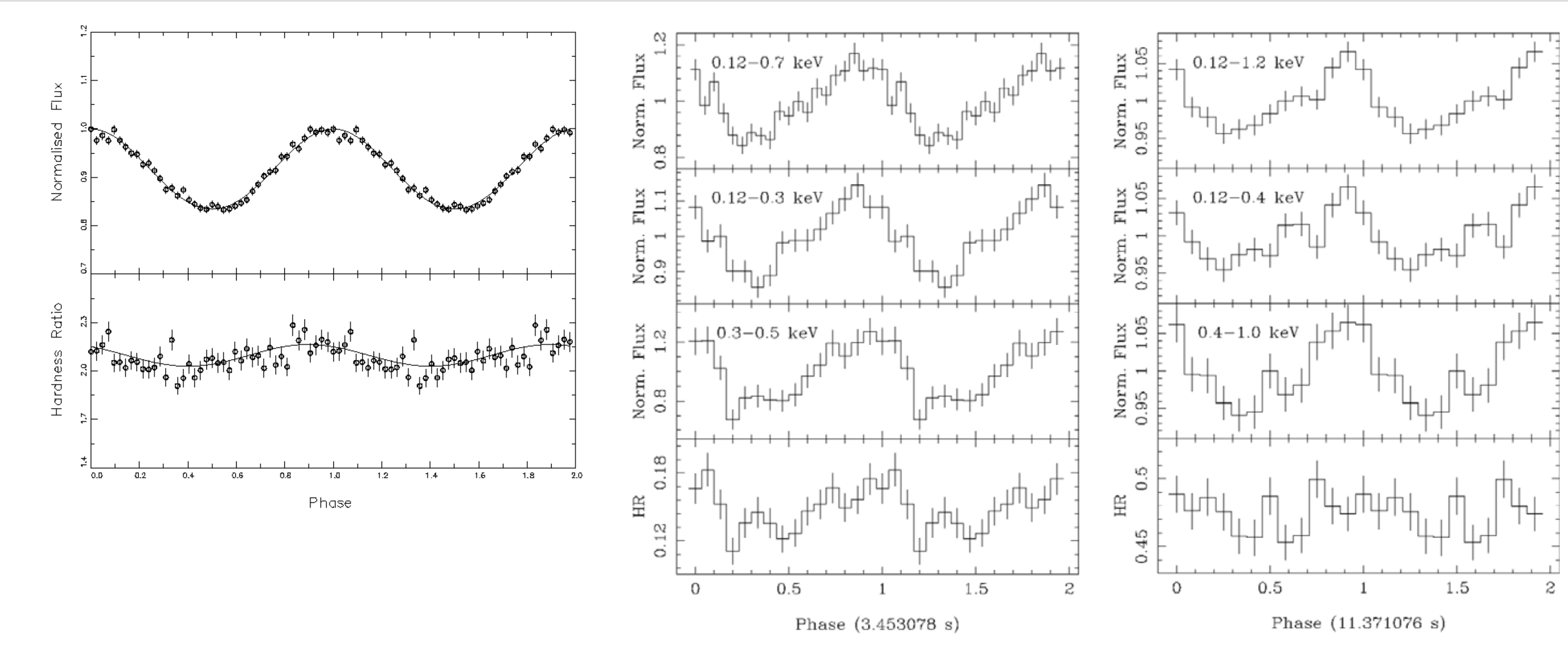
Magnetic field decay ?

Strong magnetic fields: effects on

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

More information on magnetic fields is needed !

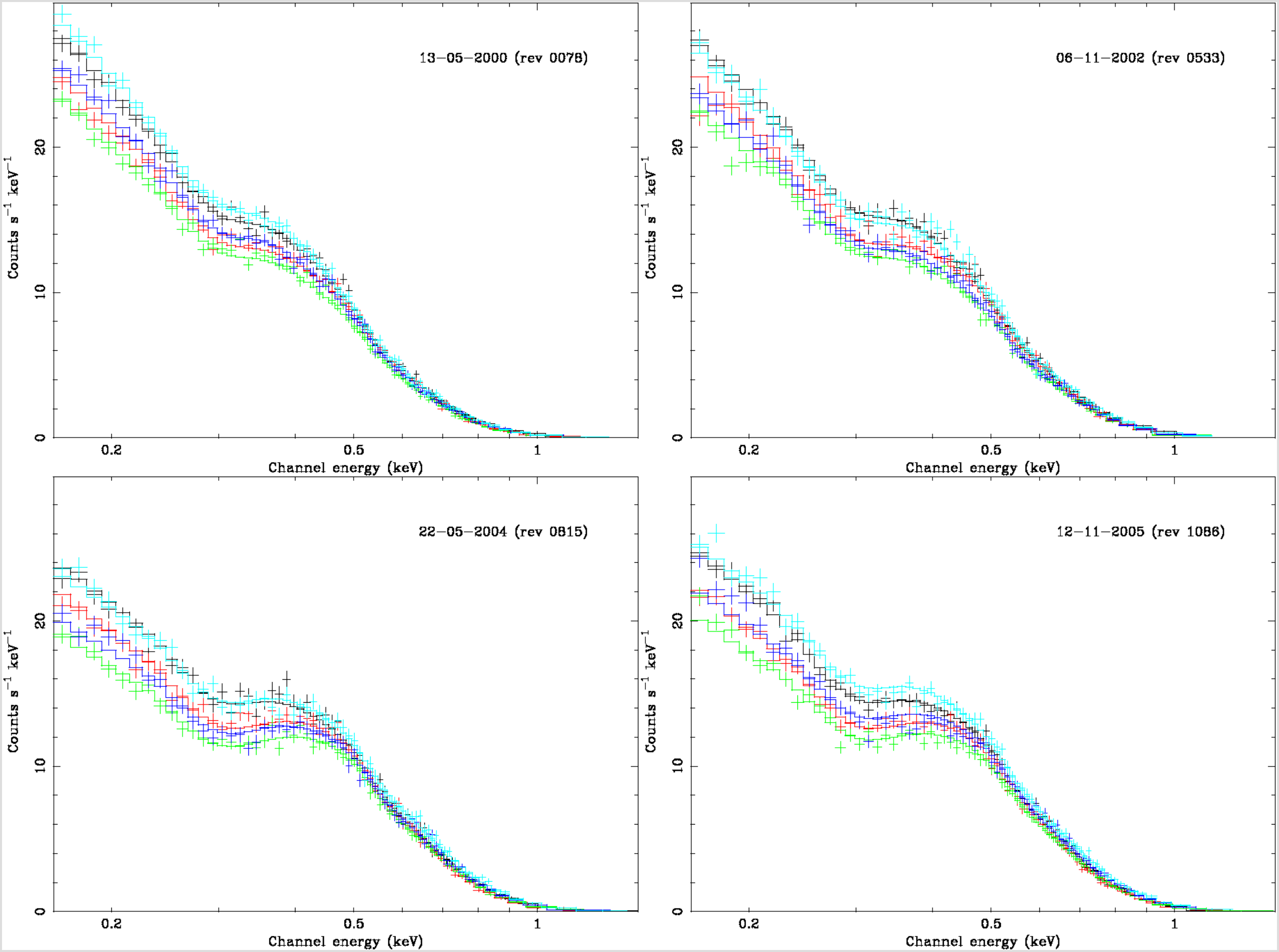
Spectral variations with pulse phase



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

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

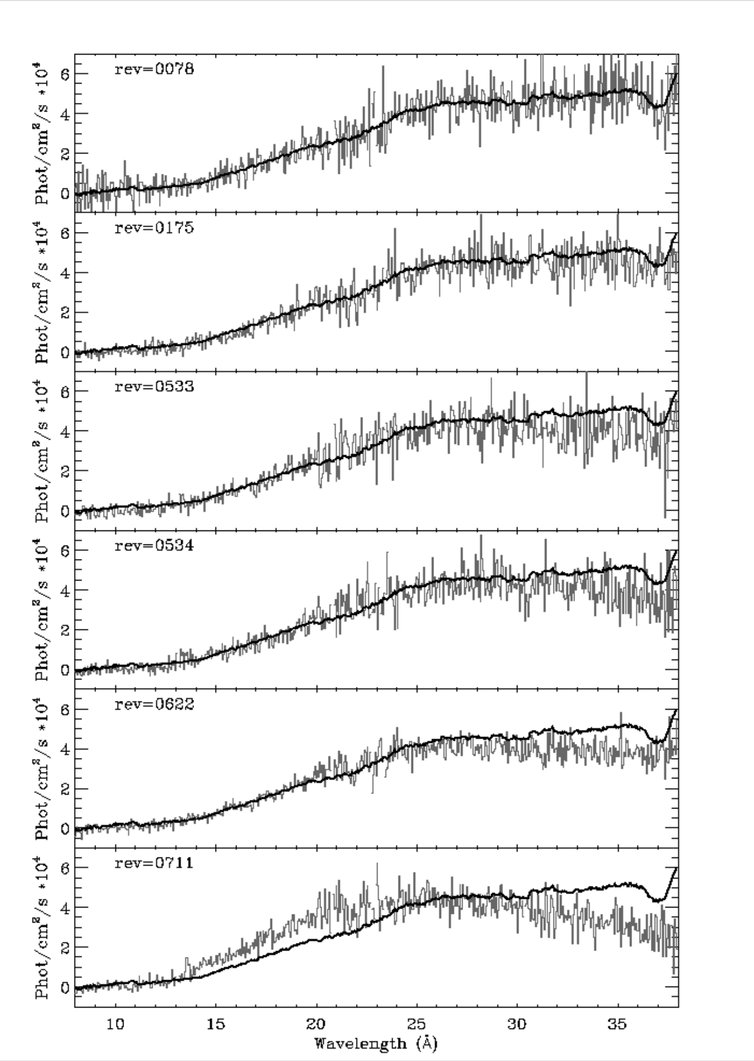
RX J0720.4–3125 pulse phase spectral variations



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

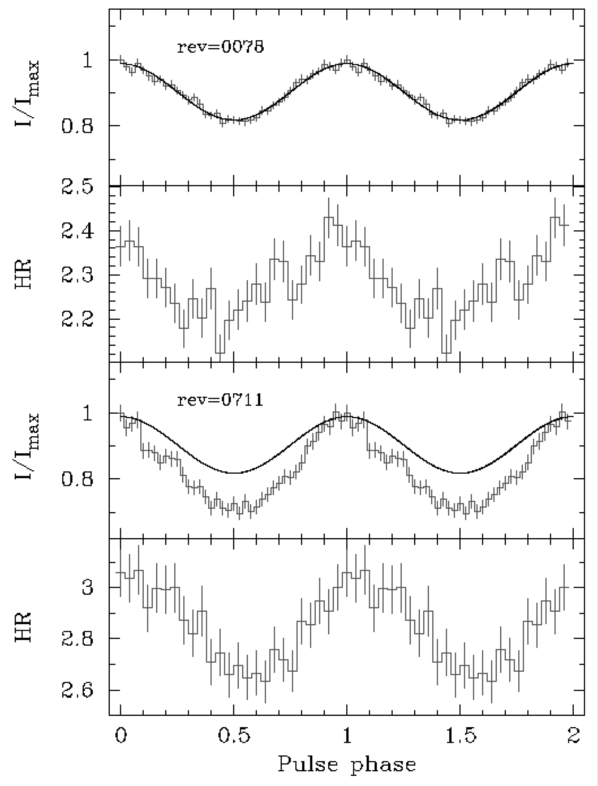
Increase at short wavelength: temperature increase
Decrease at long wavelength: deeper absorption line

XMM-Newton RGS



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

XMM-Newton EPIC-pn

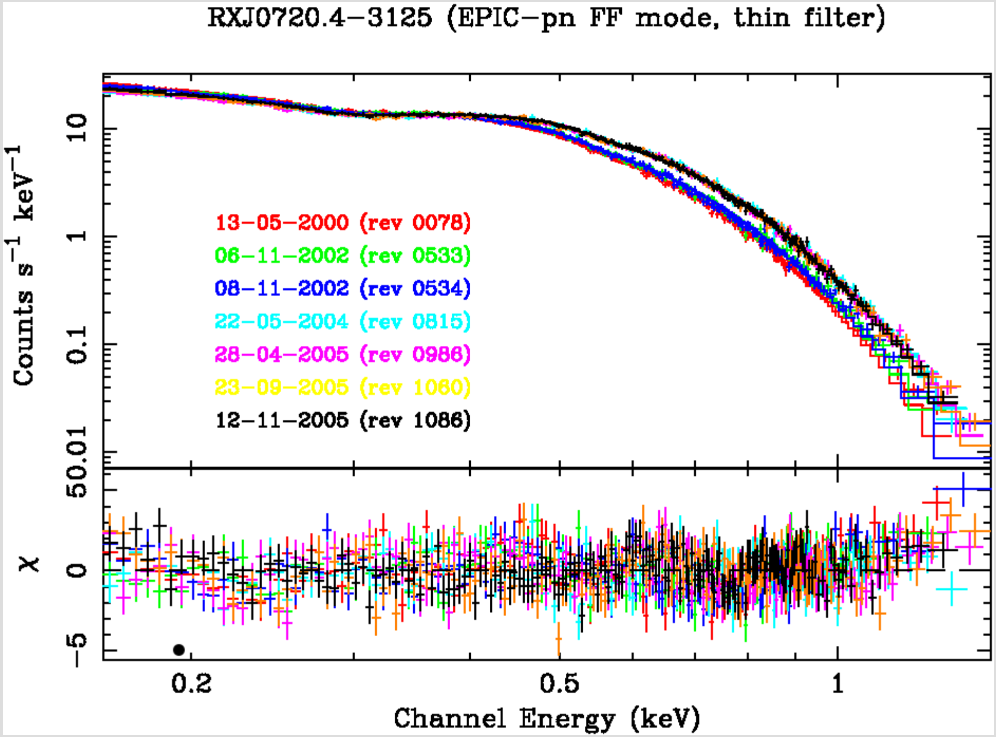


Precession of the neutron star?

de Vries et al. (2004)

RX J0720.4–3125: Spectral variations, the first 5.5 years with XMM-Newton

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

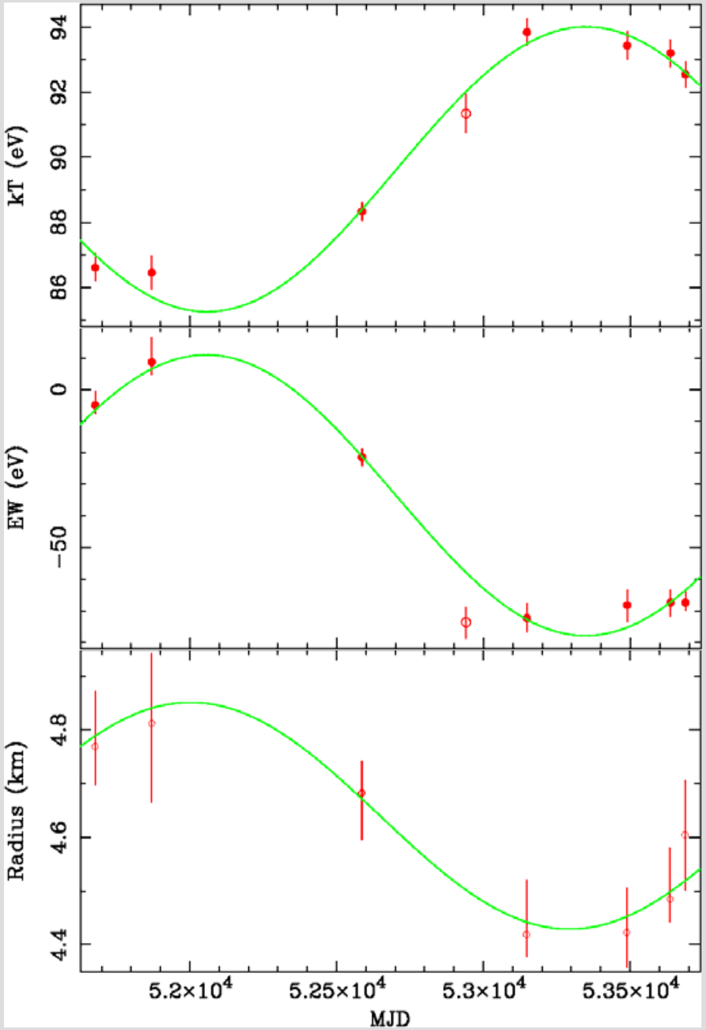
common line energy: 280 ± 6 eV
common line width: σ = 90 ± 5 eV

Long-term variations:

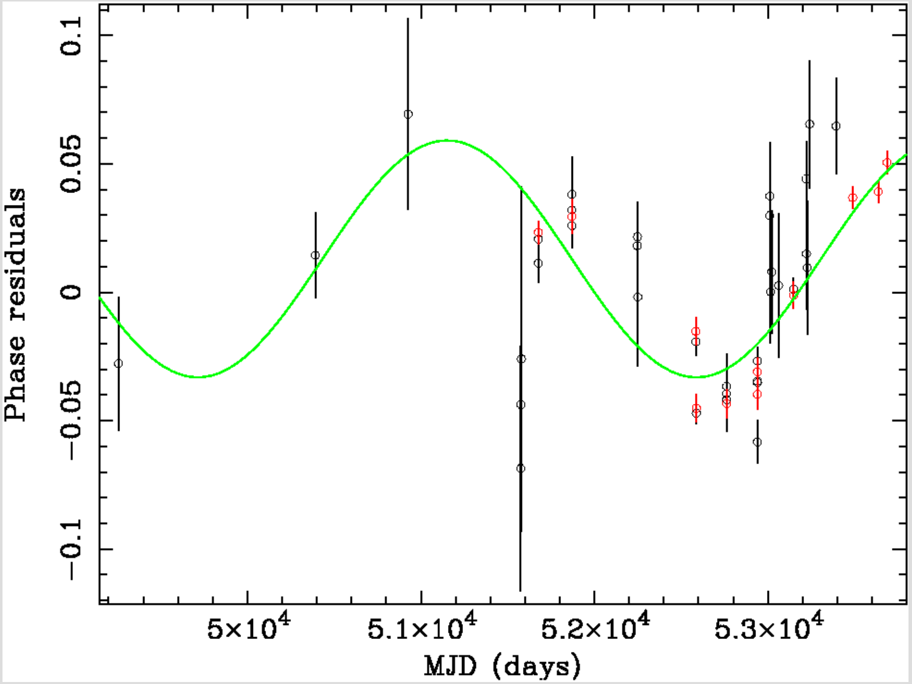
Temperature by ~7 eV
Absorption line equivalent width by ~70 eV
Radius of emission area from 4.4 km to 4.8 km (d=300pc)
But flux is constant within ±2%

RX J0720.4–3125 longterm spectral variations

Haberl et al. 2006 A&A 451, L17



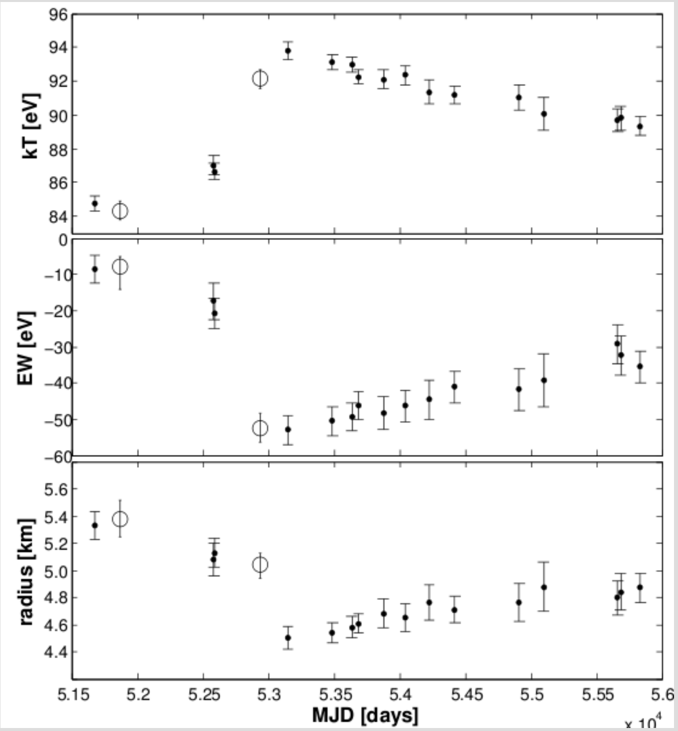
Sinusoidal variations in spectral parameters
Period 7.1 ± 0.5 years



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

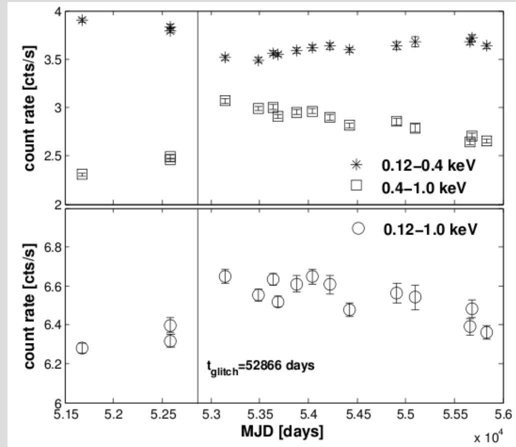
The continued spectral and temporal evolution of RX J0720.4–3125



No cyclic variations in spectral parameters with period < 12 years

kT approaches constant value higher than before "event"

The "event" is not sudden

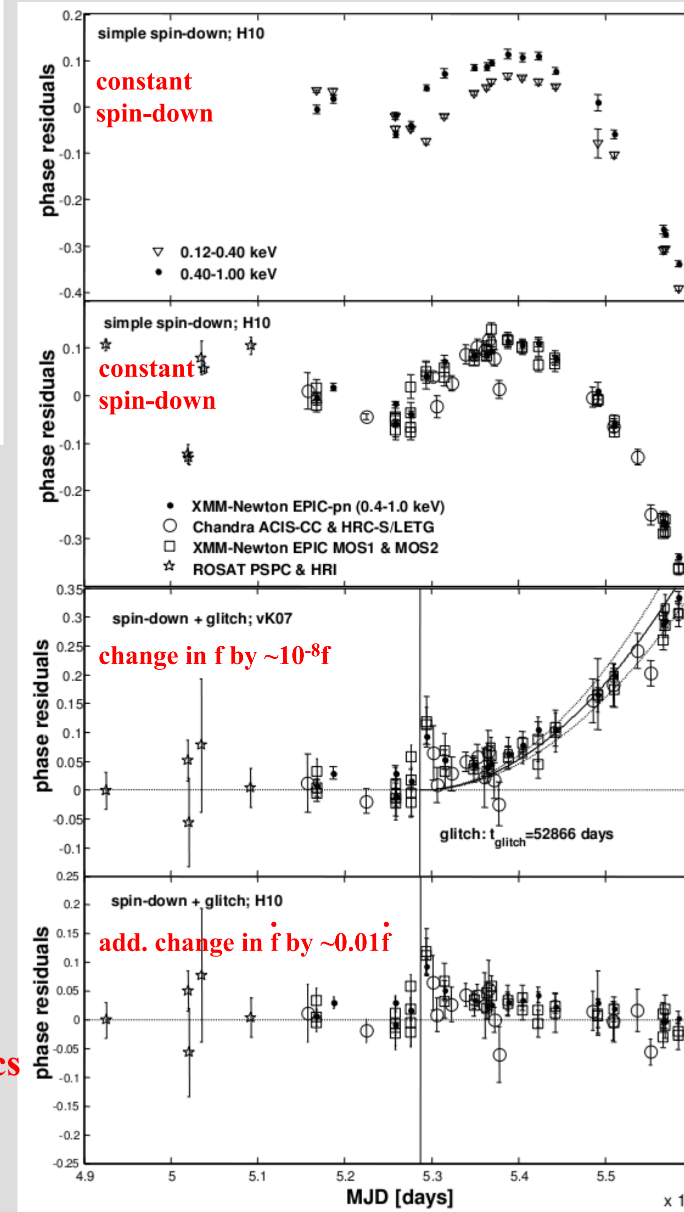


Hohle et al. 2012, MNRAS 423, 1194

Phase residuals are energy dependent.

Phase lag between soft and hard X-ray emission varies on long term time scale.

Soft and hard emission originates from different locations.
Two hot spots with somewhat different emission characteristics (kT, size, B?).
Non-cyclic movement of spots ?



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^{31-32} erg s^{-1}
- Constant X-ray flux on time scales of years
- No obvious association with SNR
- No (faint?) radio emission (RBS1223, RBS1774)
- All are X-ray pulsars (3.39 – 11.37 s)
- Proper Motion is inconsistent with heating by accretion from ISM

Object	$T/10^6$ K	kT/eV	P/s	Optical	distance/pc	F_x/cgs	L_x/cgs
RX J0420.0–5022	0.51	44	3.45	B = 26.6	(300–370)	$3.3\cdot10^{-13}$	$4.4\cdot10^{30}$
RX J0720.4–3125	0.99–1.10	85–95	8.39	B = 26.6	280 +210/–85	$9.7\cdot10^{-12}$	$7.9\cdot10^{31}$
RX J0806.4–4123	1.11	96	11.37	B > 24	(210–275)	$2.4\cdot10^{-12}$	$1.7\cdot10^{31}$
RX J1308.8+2127*	1.00	86	10.31	m_{50ccd} = 28.6		$3.2\cdot10^{-12}$	$9.6\cdot10^{31}$
RX J1605.3+3249	1.11	96	3.39	B = 27.2	(300–415)	$6.1\cdot10^{-12}$	$9.4\cdot10^{31}$
RX J1856.5–3754	0.73	62	7.06	B = 25.2	123 +11/-15	$1.3\cdot10^{-11}$	$2.3\cdot10^{31}$
RX J2143.0+0654**	1.17	102	9.44	B = 27.4	(365–455)	$2.8\cdot10^{-12}$	$5.6\cdot10^{31}$

*1RXS J130848.6+212708 = RBS1223 (assumed d=500 pc) ** 1RXS J214303.7+065419 = RBS 1774

Flux and Luminosity for 0.1-2.4 keV

Conclusions

- The idealized picture of a neutron star with uniform surface temperature and dipolar magnetic field is too simple.
- Strong magnetic fields
  - influence surface temperature distribution (hot poles – assymetries)
  - change thermal evolution (cooling models)
  - field decay?
- We need to better understand our systematic errors
  - ages, distances
- We need to better understand the thermal emission from neutron stars
  - neutron star atmosphere (condensation?)