Exploring the Surface of Isolated Neutron Stars with XMM-Newton

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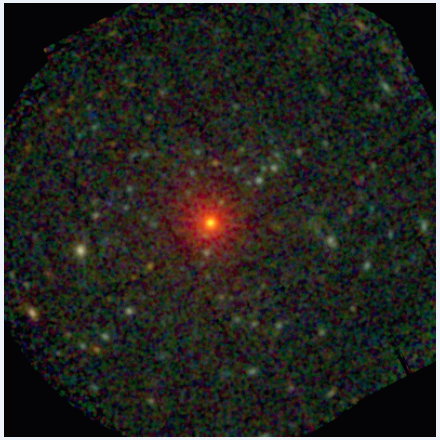
Thermally emitting isolated neutron stars
- **Surface temperature distributions**
- **Magnetic fields**



XMM-Newton 10th Anniversary

ESAC, Villafranca del Castillo, Madrid, Spain

10th December 2009

Some history

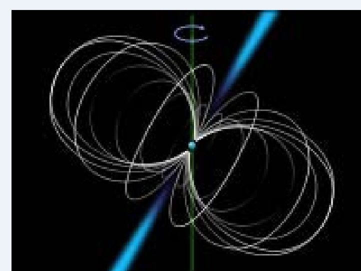
1932 James Chadwick
Discovery of neutron (Nobel Prize in Physics 1935)

1931 Lew Landau
Proposal for the existence of neutron stars

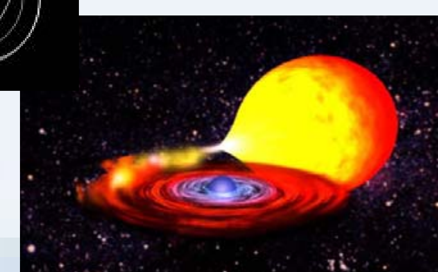
1933 Walter Baade and Fritz Zwicky
Neutron stars as end products of stellar evolution created in supernova explosion
$p + e^{-} + 0.78\ \mathrm{MeV} \rightarrow n + \nu_e$

1939 Robert Oppenheimer and George Volkoff
Theoretical model for a neutron star
10 km radius, nuclear density – 10^9 tons per cm^{-3}

1967 Jocelyn Bell and Antony Hewish
Discovery of radio pulsars
rotation-powered



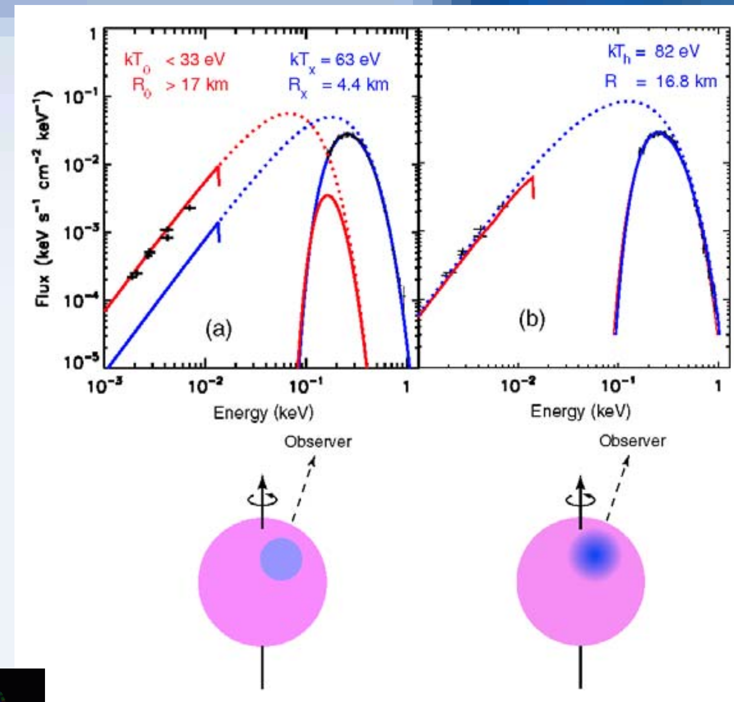
1971 Riccardo Giacconi et al.
Discovery of X-ray binary pulsar Cen X-3
powered by accretion of matter from companion star

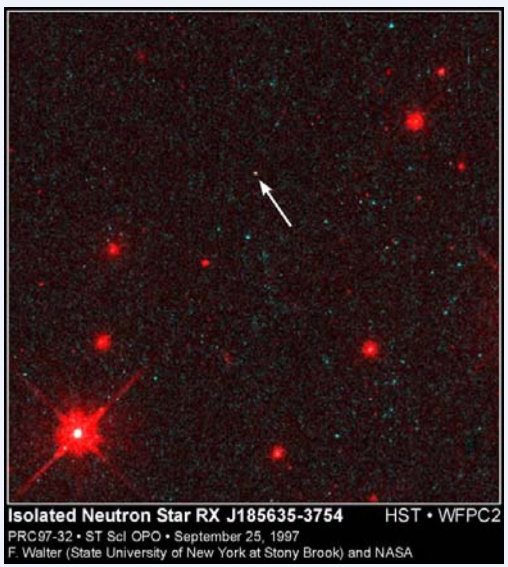


Can we see isolated neutron stars directly ?

expected size: 10 km radius
neutron star @ 100 pc $\leftrightarrow$ dust particle (1μm) on Moon

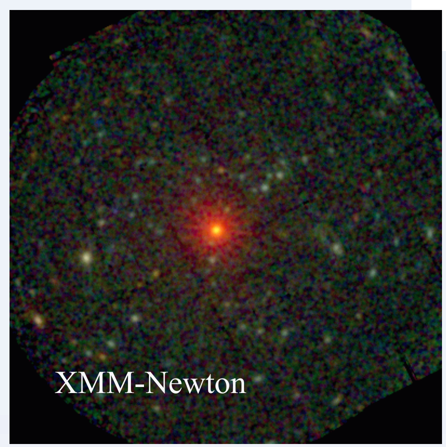
expected surface temperature: Million degrees (100 eV)
$L = A\, \sigma\, T^4$
maximum radiation in soft X-ray band
inhomogeneous temperatur distribution → pulsations





Optical

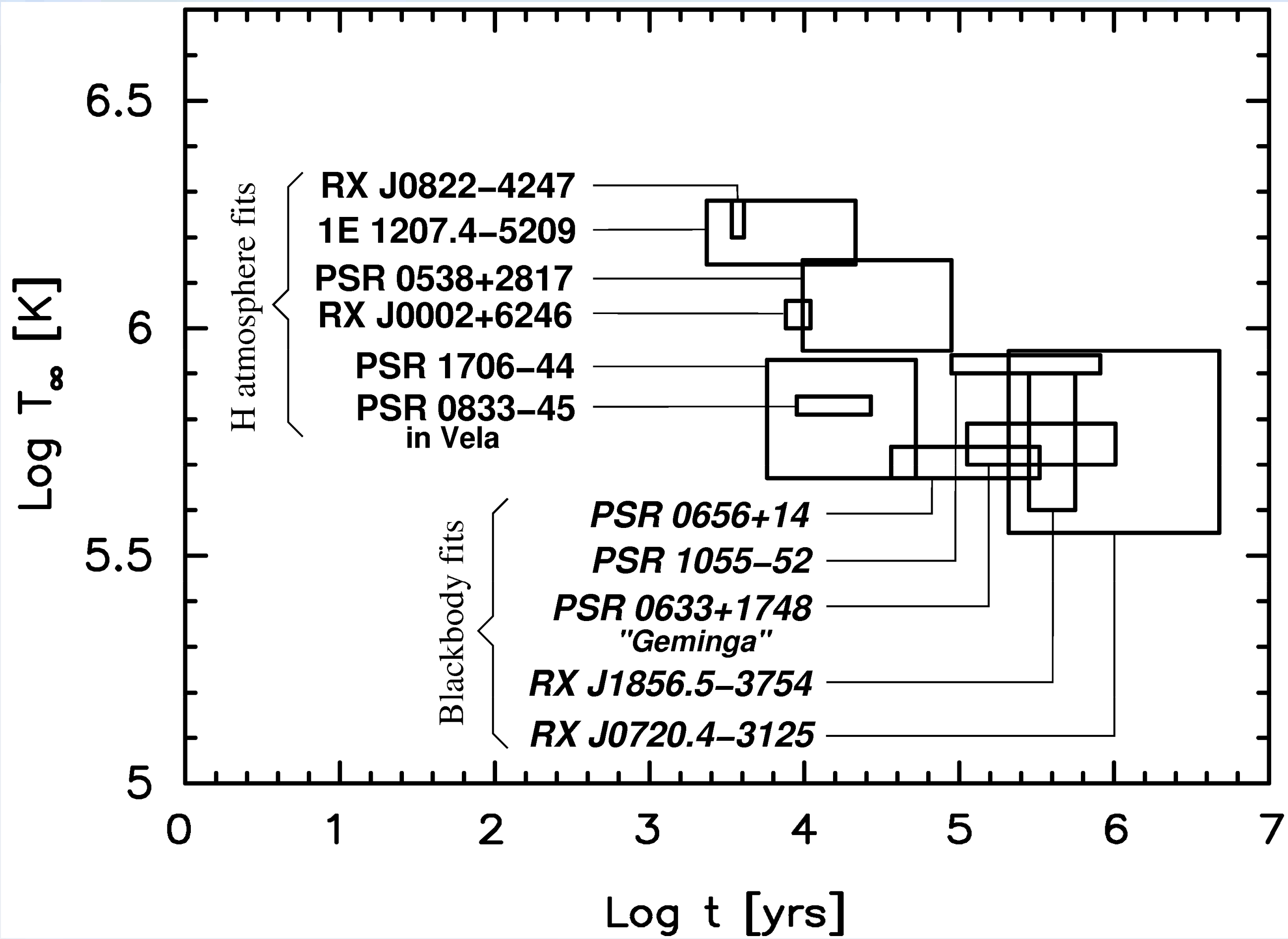
RX J0720.4-3125



RX J1856.5-3754

X-rays

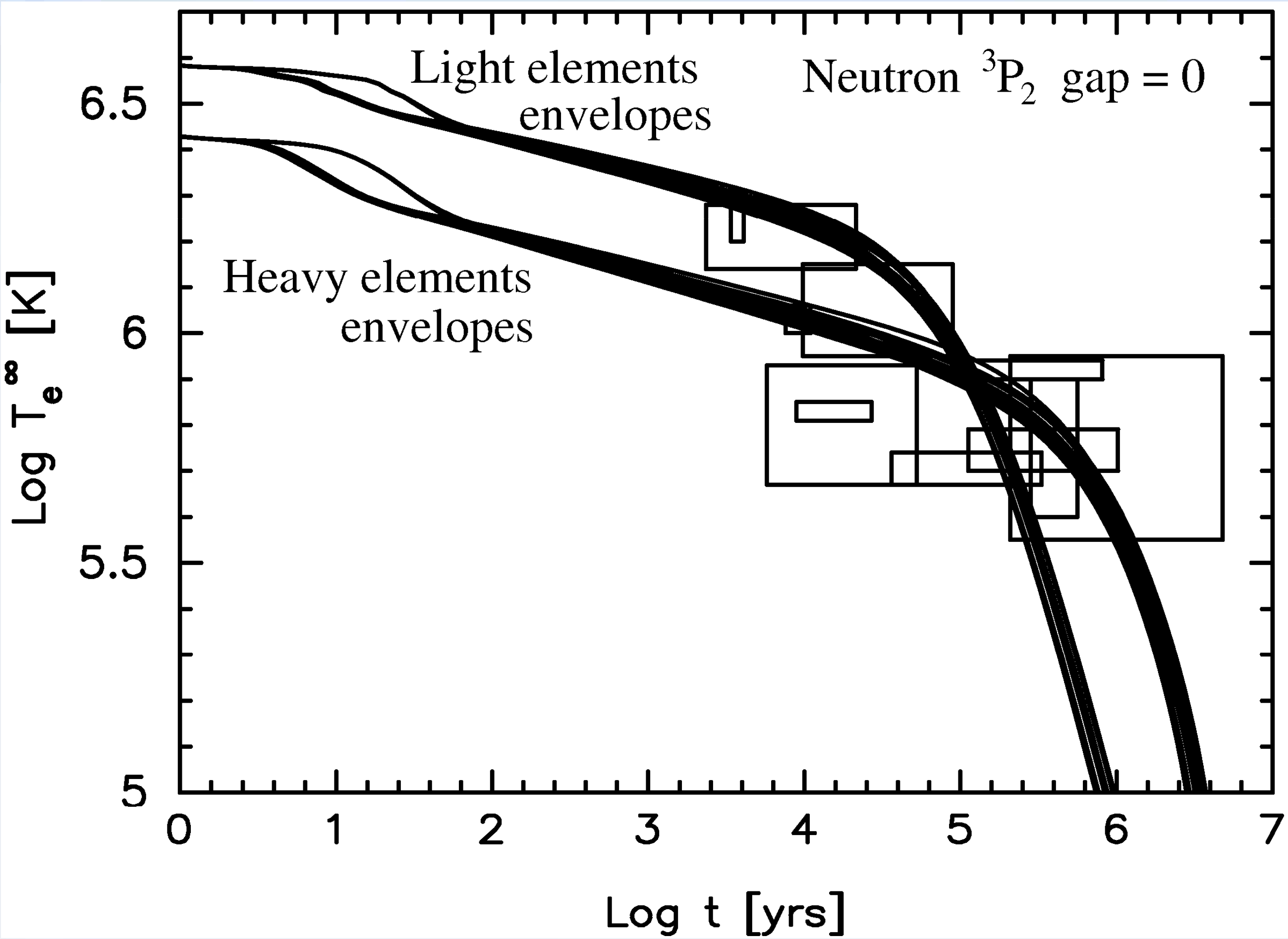
Thermally emitting neutron stars



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

Thermally emitting neutron stars



Modelling of NS cooling:
- **EOS**
- **Superfluid properties**
- **Stellar mass**
- **Envelope composition**

Page et al. 2004
(ApJS 155, 623)

- **Cooling by neutrino emission from interior and photon emission from surface**
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Middle-aged pulsars: The Three Musketeers

- **First X-ray detections with Einstein Observatory**
- **Timing and spectral analysis with ROSAT**
- **ROSAT + ASCA: Three-component model**

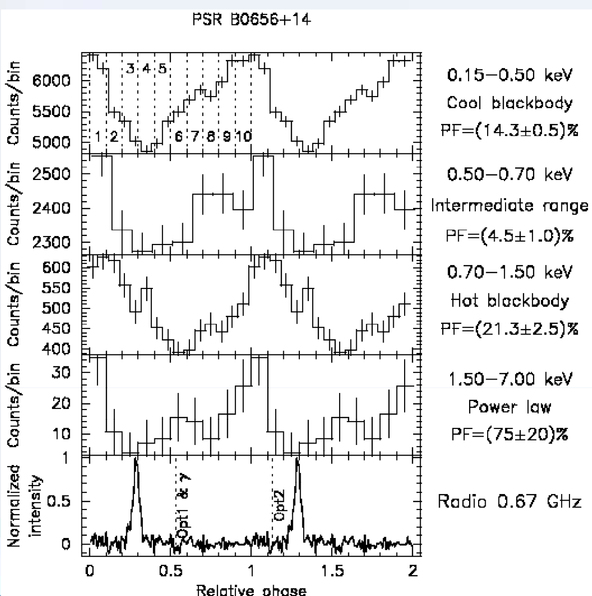
  Cool BB (bulk of the star surface)

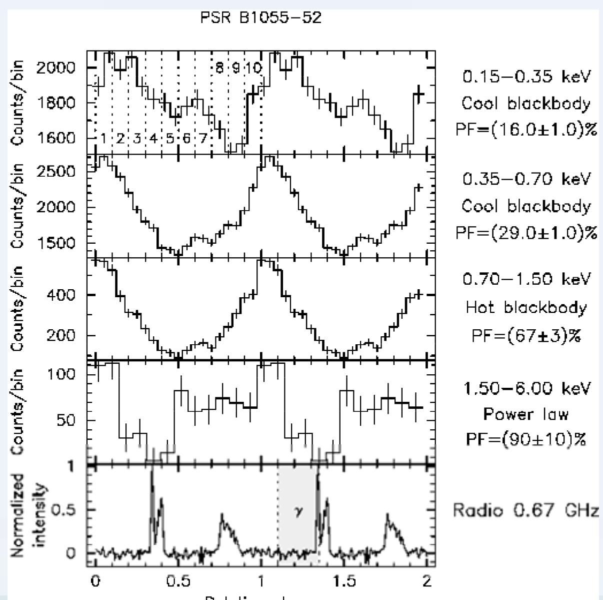
  Hot BB (smaller hot spots)

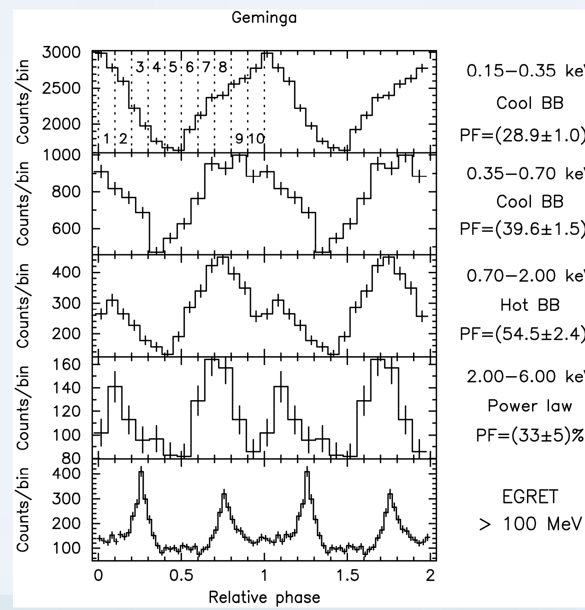
  Powerlaw (magnetosphere)

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

- **XMM-Newton: Pulse phase spectroscopy**

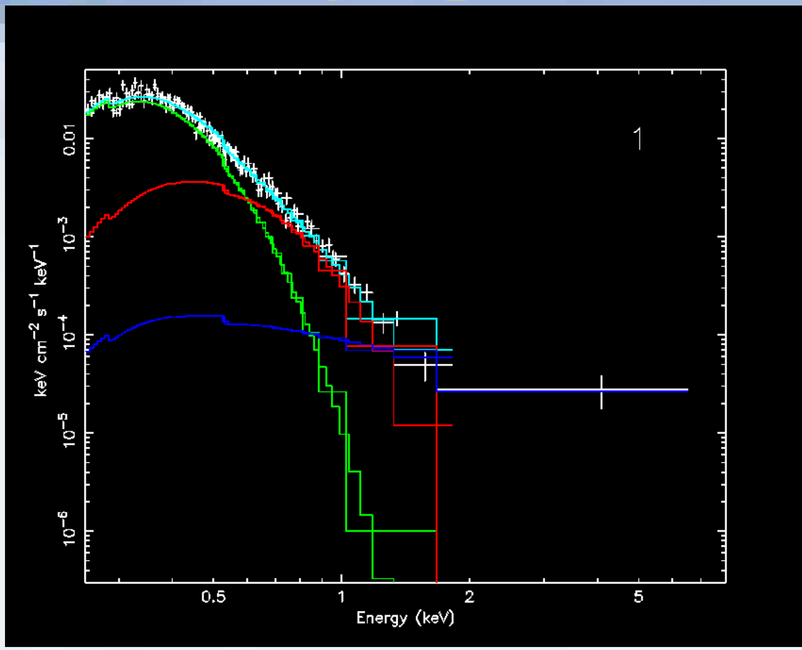




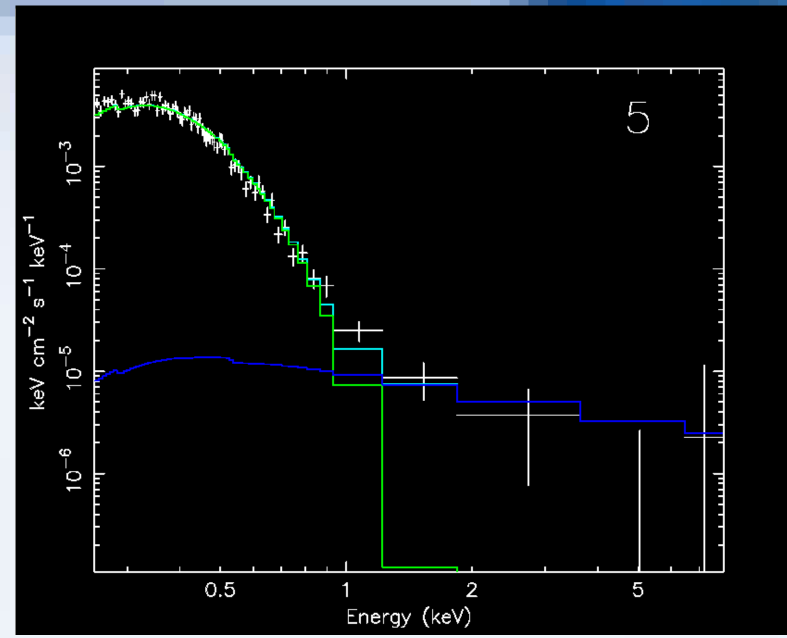


De Luca et al. 2005 (ApJ 623, 1051)

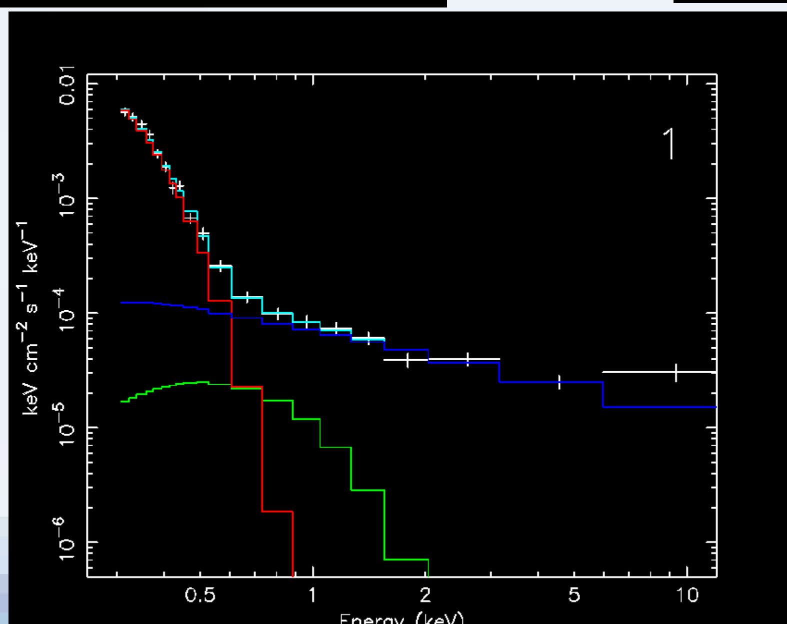
Middle-aged pulsars: The Three Musketeers



PSR B0656+14



PSR B1055-52



Geminga

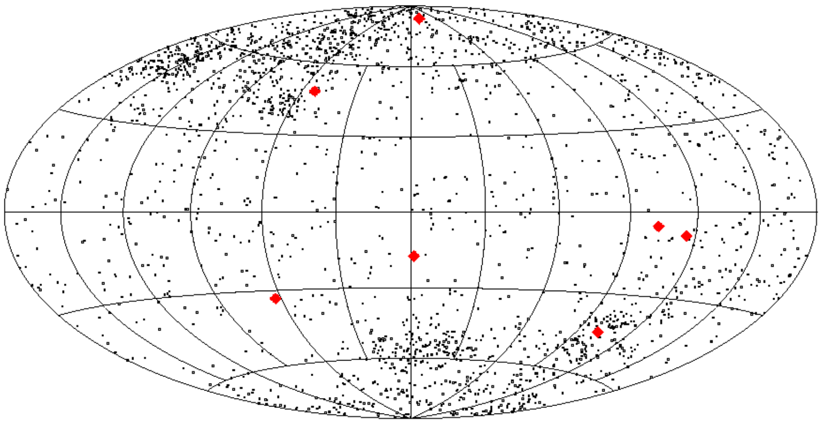
Cool blackbody
Hot blackbody
Powerlaw

Challenge for the simple model based on centered dipole geometry

Radio-quiet isolated neutron stars: The Magnificent Seven

- Blackbody-like soft X-ray spectra
- No non-thermal hard X-ray emission
- No radio emission
- Proper Motion is inconsistent with heating by accretion from ISM
- Low ISM absorption ↔ nearby
- Probably all are X-ray pulsars (~10s)

A Legacy of ROSAT:



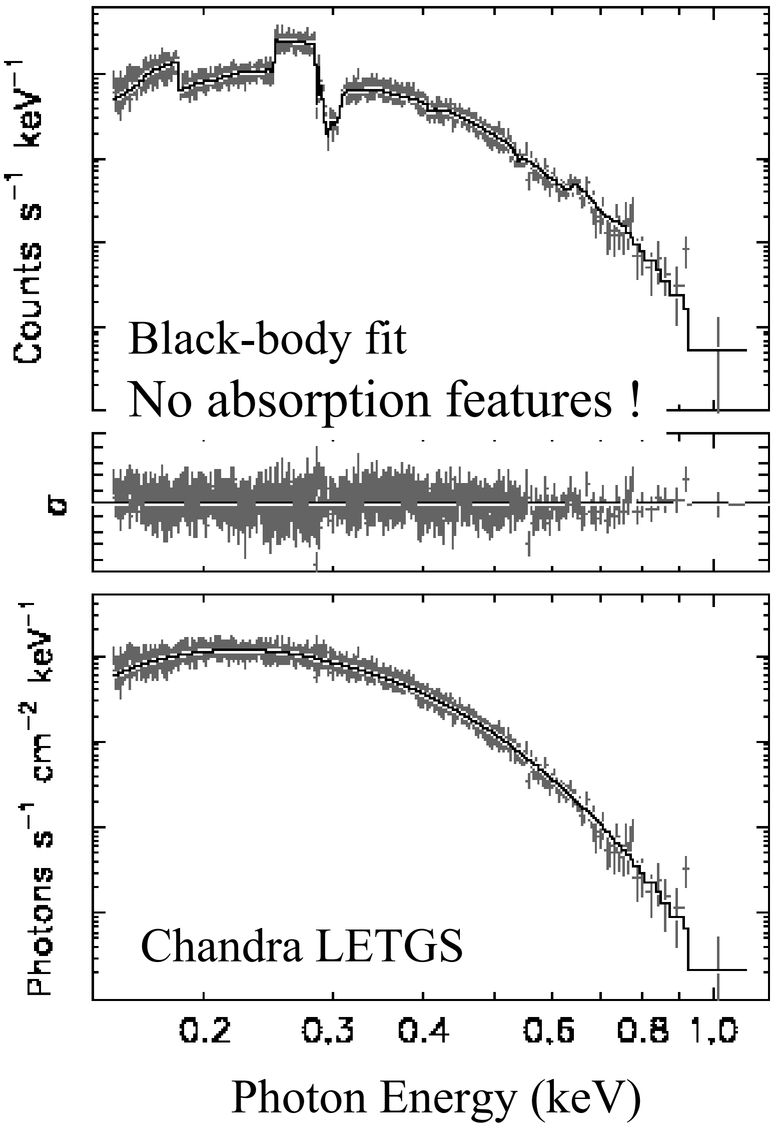
Soft X-ray spectrum + faint in optical

Best cases 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 > 27.5		
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		

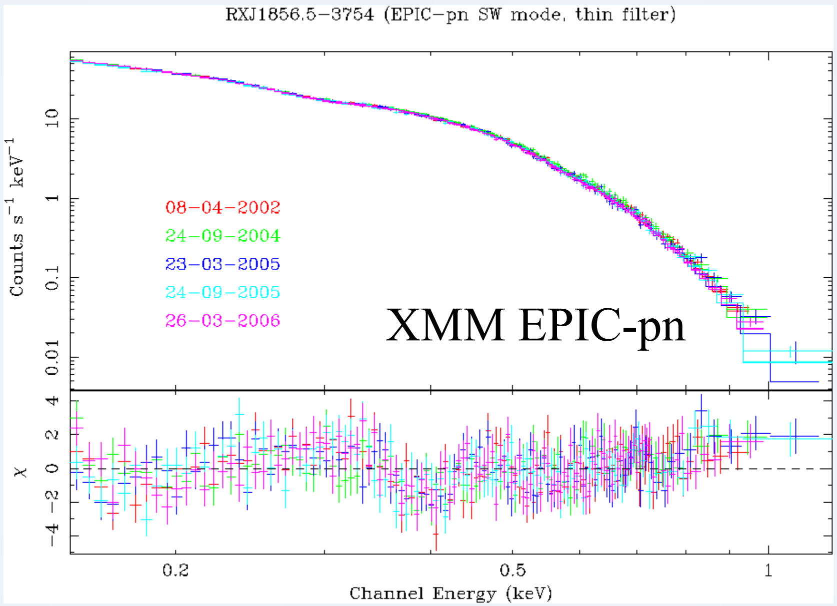
RX J1308.8+2127 = 1RXS J130848.6+212708 = RBS1223 RX J2143.0+0654 = 1RXS J214303.7+065419 = RBS 1774

The X-ray spectrum of RX J1856.5–3754



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

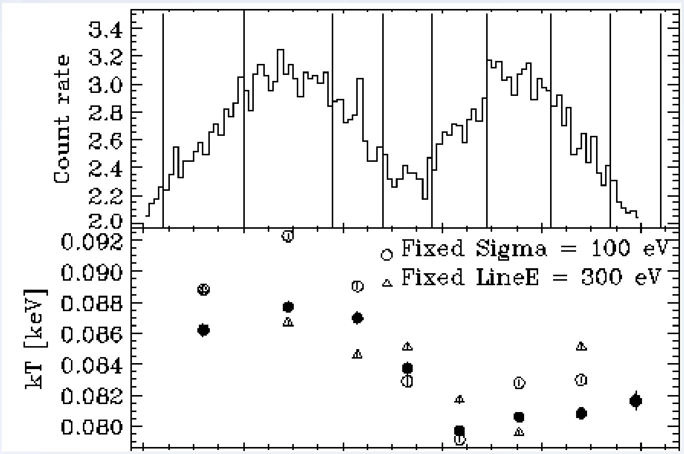
Burwitz et al. (2003, 2004)



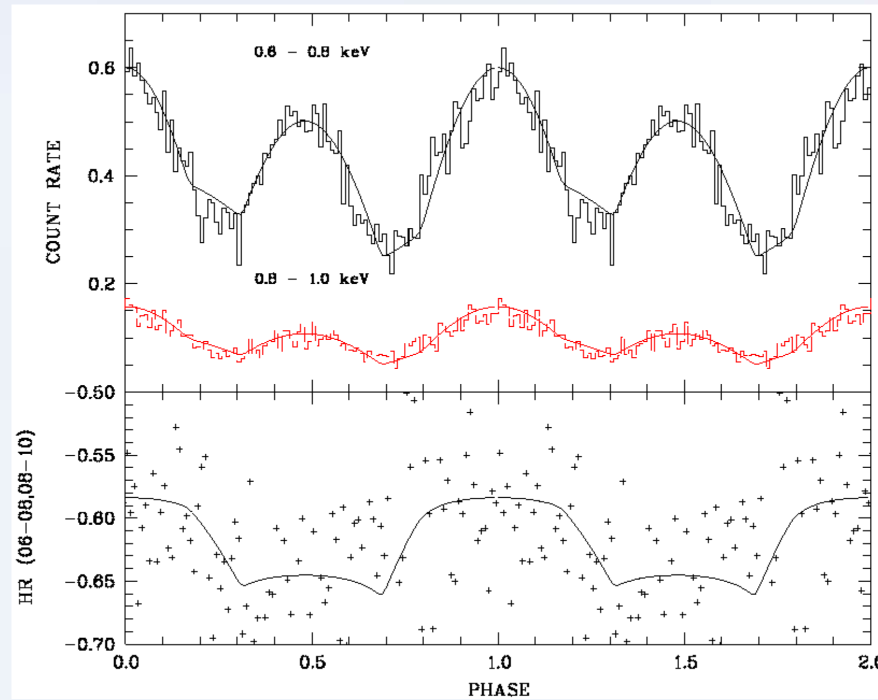
Spectrum constant over time scales of years

Spectral variations with pulse phase: RBS 1223

Pulse phase spectroscopy



Pulse profile modelling



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

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

offset $\sim 20^o$

Schwope et al. (2005)

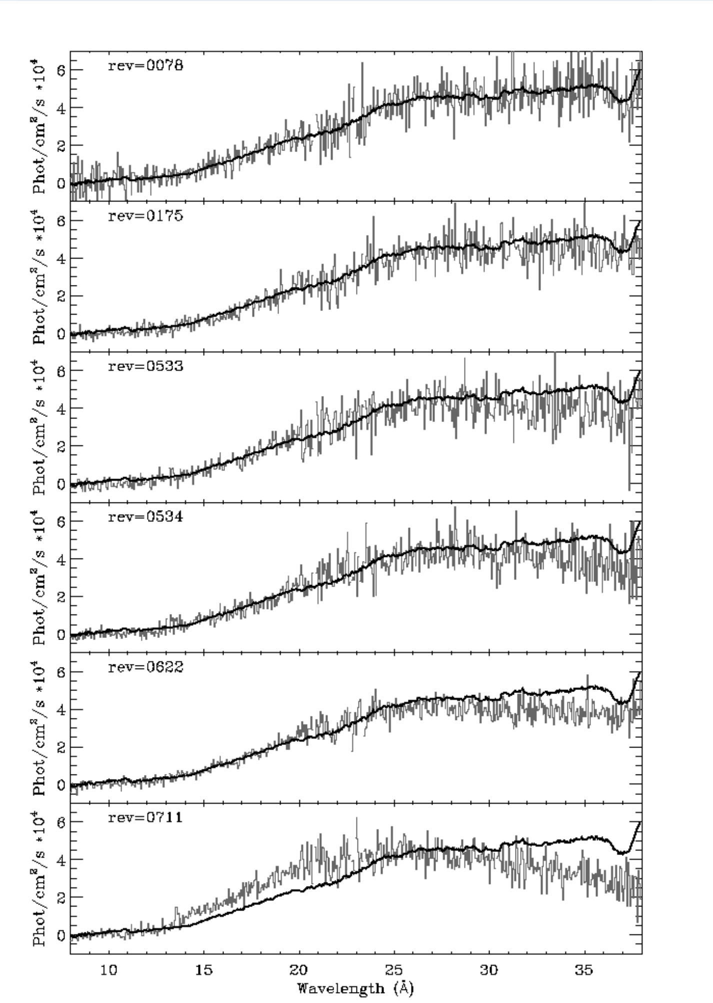
Two spots with different parameters and not antipodal!

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

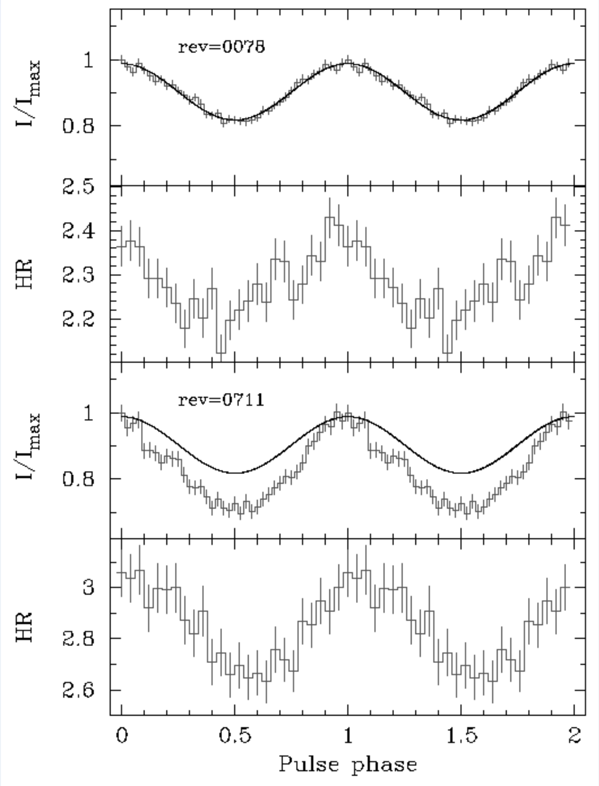
Increase at short wavelength: temperature increase
Decrease at long wavelength: deeper absorption line

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

XMM-Newton RGS



XMM-Newton EPIC-pn

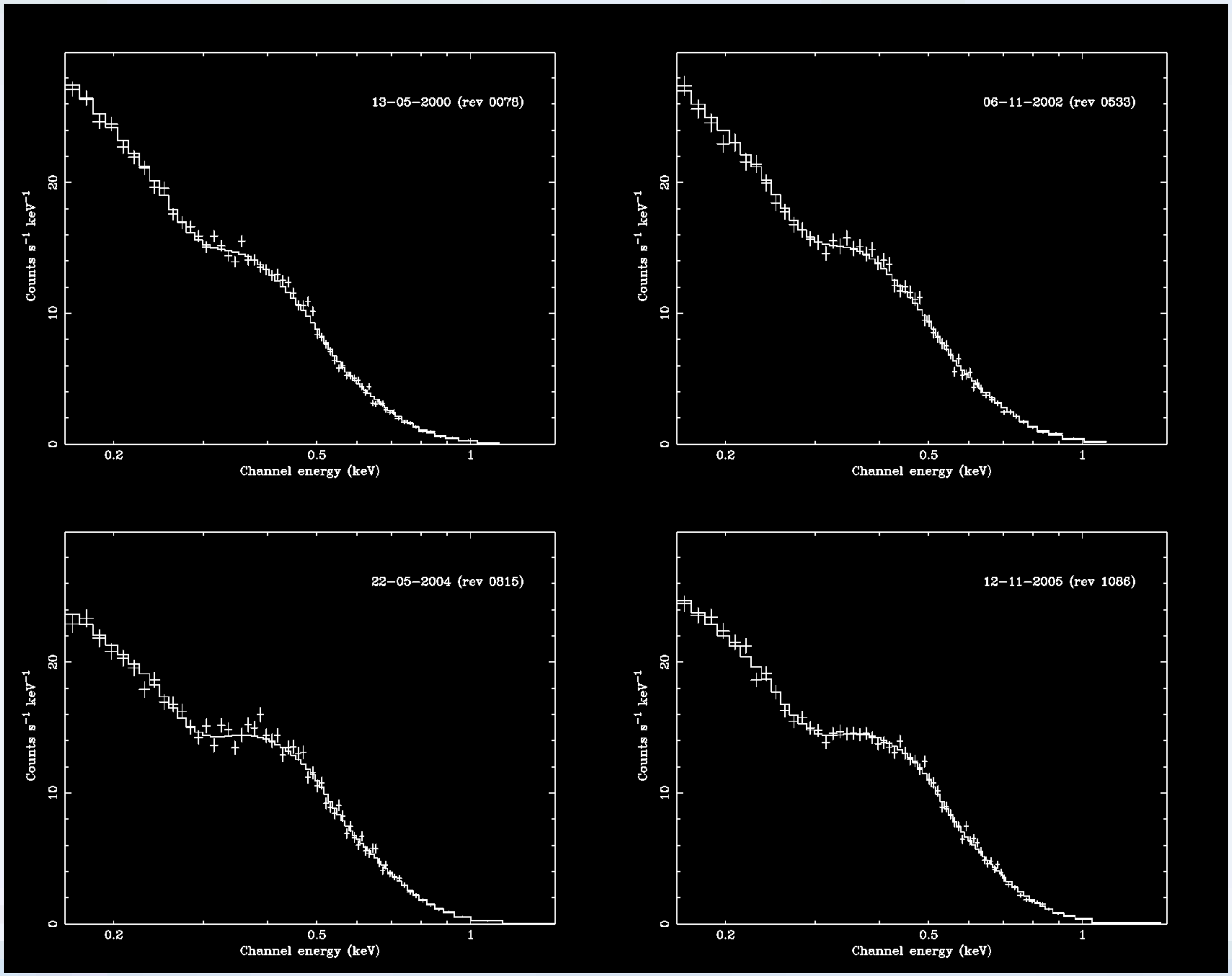


Precession of the neutron star?

de Vries et al. (2004)

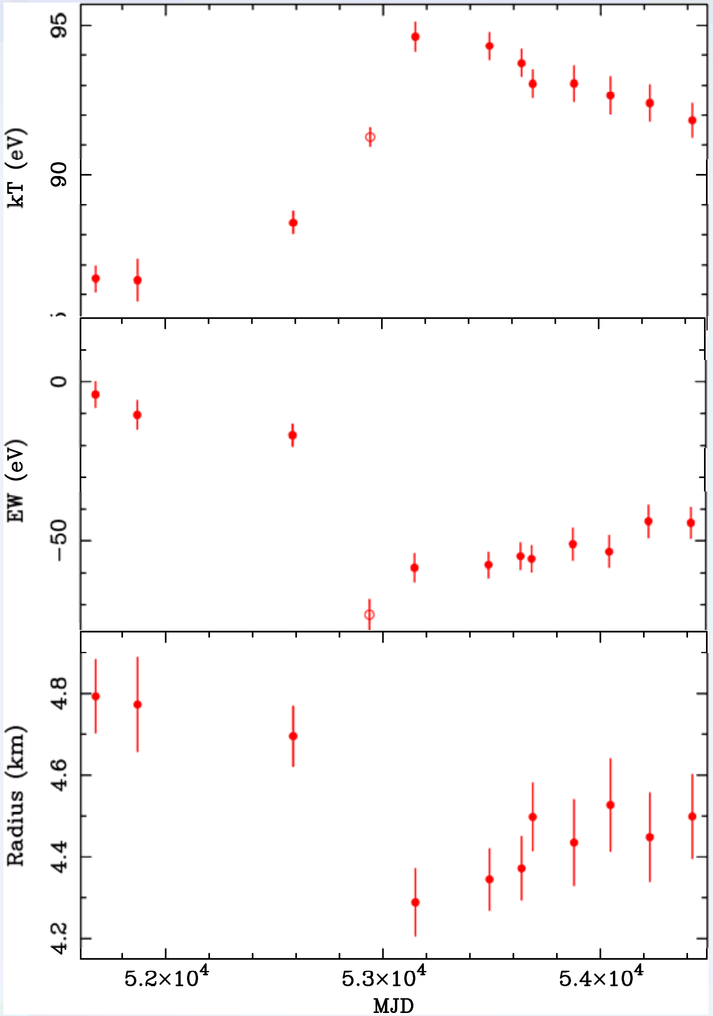
RX J0720.4-3125 spectral variations

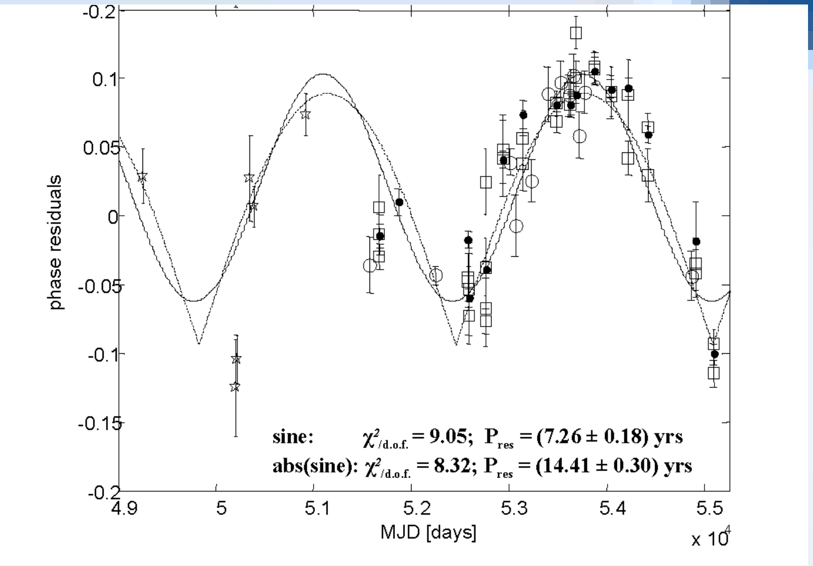
with pulse phase and on time scales of years

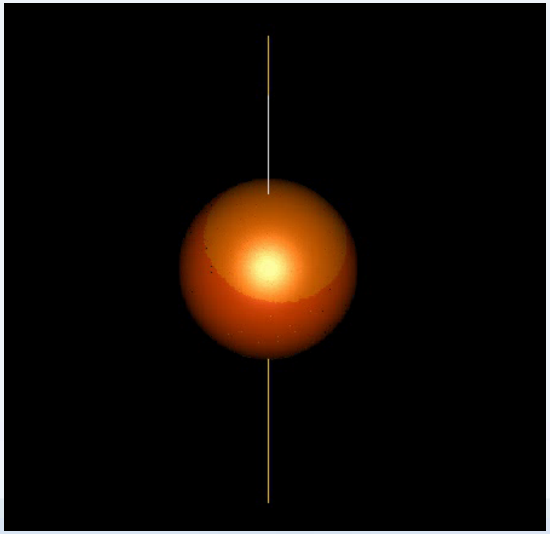


RX J0720.4-3125: A precessing neutron star?

Hohle et al. in preparation

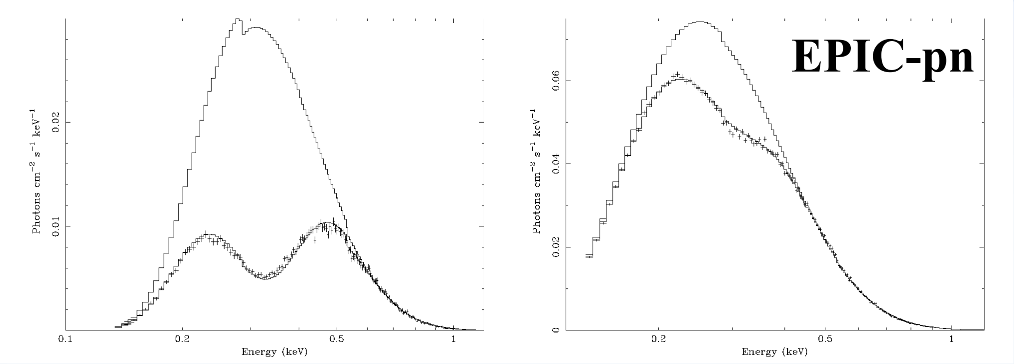




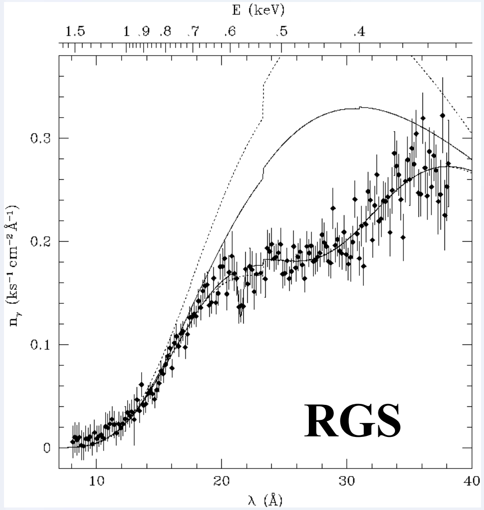


XMM-Newton observations of the M7: absorption features

RBS 1223
EW = 150 eV
Variations of line parameters with pulse phase

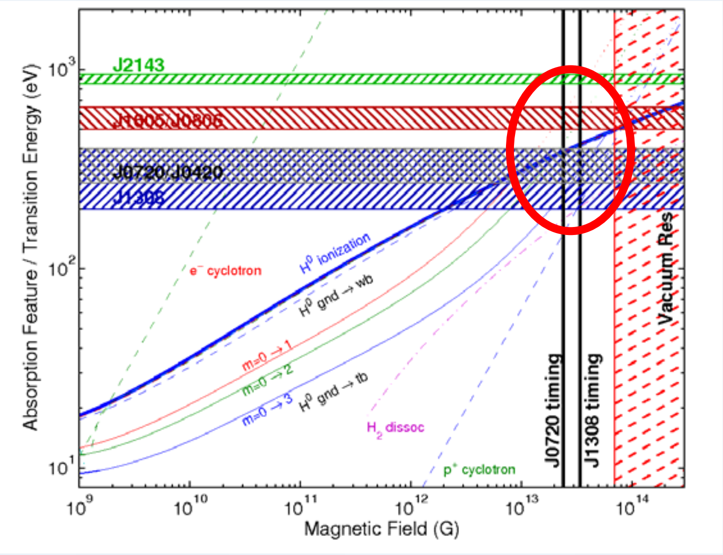


RX J0720.4-3125
EW = 40 eV
Variable with pulse phase and over years



RX J1605.3+3249
$E_{line} \approx 450$ eV
Van Kerkwijk et al. (2004)
EPIC-pn:
evidence for multiple lines

Proton cyclotron absorption line ?
Atomic line transitions ?



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

van Kerkwijk & Kaplan 2007
Ap&SS 308, 191

Summary - Magnetic fields

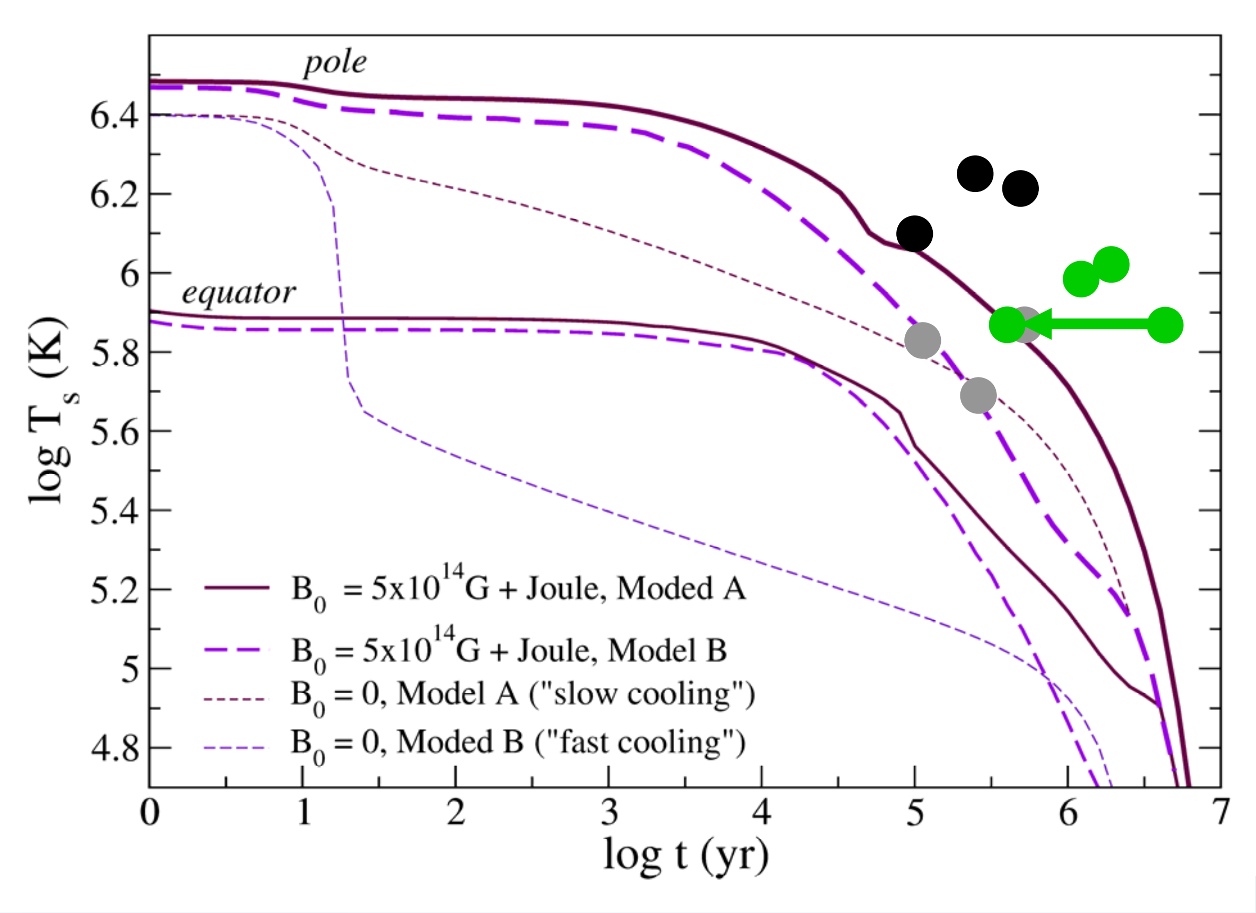
- Magnetic dipole braking → $B = 3.2 \cdot 10^{19}\ (P \cdot dP/dt)^{1/2}$
- Proton cyclotron absorption → $B = 1.6 \cdot 10^{11}\ E(eV)/(1-2GM/c^2R)^{1/2}$

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%	0.55(30)	430/306 a)	2.5	8.6/6.1
RX 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	–
RX J2143.0+0654	9.43	4%	0.41(18)	750	2.0	15

a) Spectral fit with single line / two lines
b) With single line / three lines at 400 eV, 600 eV and 800 eV

Cooling of strongly 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

Strong effects of magnetic field on

- **heat transport → surface temperature distribution**
- **the thermal evolution**

Summary and outlook

Isolated cooling neutron stars

The Three Musketeers

$\tau \approx 10^{5\text{-}6}$ years, B $\approx$ (1-5) x 10^6 G (dipole braking)

The Magnificent Seven

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

10^{13} G (dP/dt + absorption features, factor of 2-3 difference)

Influence of the magnetic field on

surface temperature distribution

thermal evolution

The idealized picture of a neutron star with uniform surface temperature and dipolar magnetic field is too simple.

Stability of XMM-Newton instruments

Further monitoring of RX J0720.4–3125: Periodic behaviour?

Period evolution of M7 stars: Relation $B_{db} \leftrightarrow B_{cyc}$