X-ray Observations of Rotation Powered Pulsars

George Pavlov (Penn State)

Oleg Kargaltsev (George Washington Univ.)
Martin Durant (Univ. of Toronto)
Bettina Posselt (Penn State)

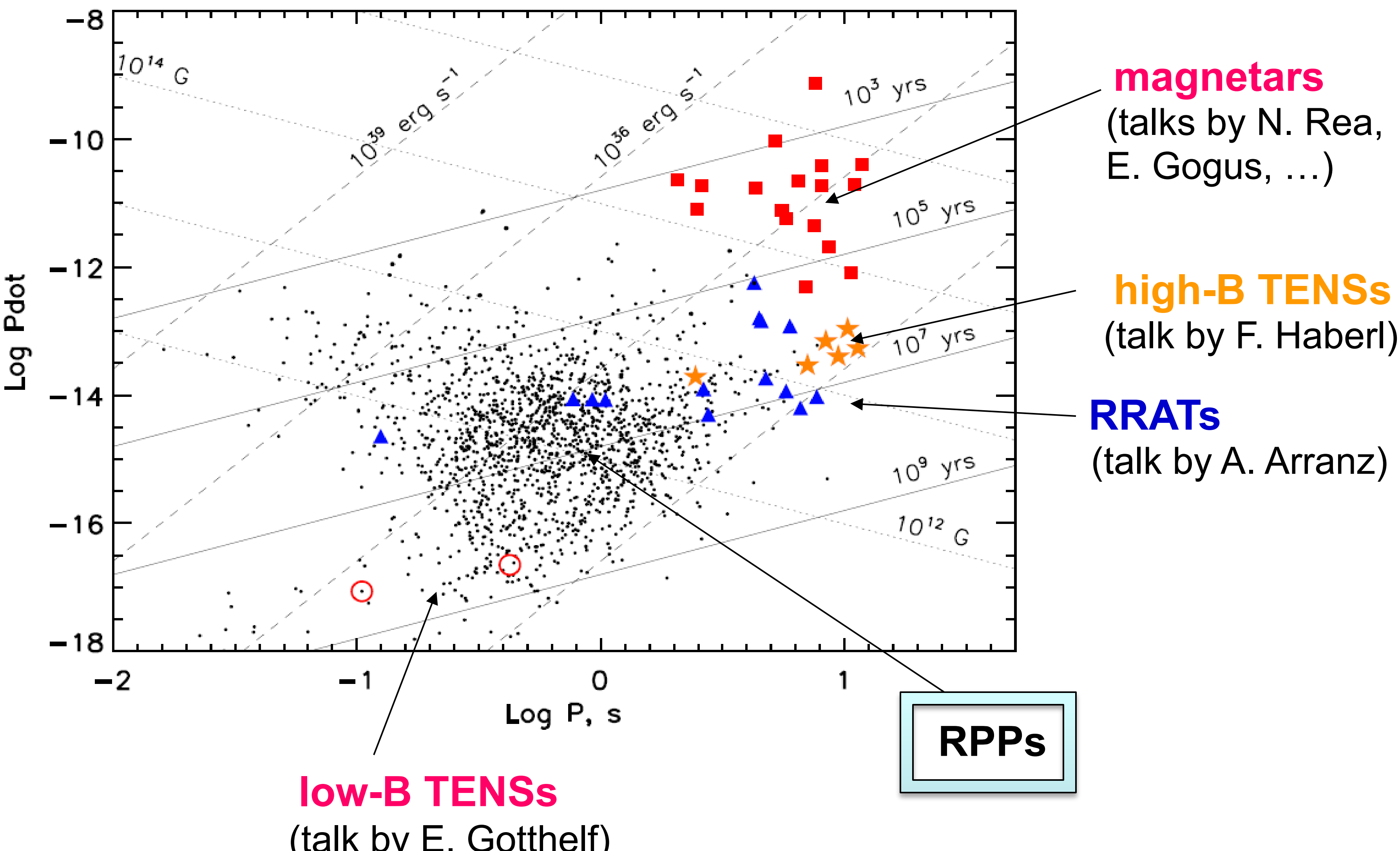
Isolated neutron stars - no accretion

Diverse population:

Rotation powered pulsars (**RPP**s)
Thermally emitting NSs (**TENS**s = XDINSs = XINSs = M7)
Anomalous X-ray pulsars (**AXP**s)
Soft gamma repeaters (**SGR**s)
Central Compact Objects (**CCO**s) in SNRs
Rotating radio transients (**RRAT**s)

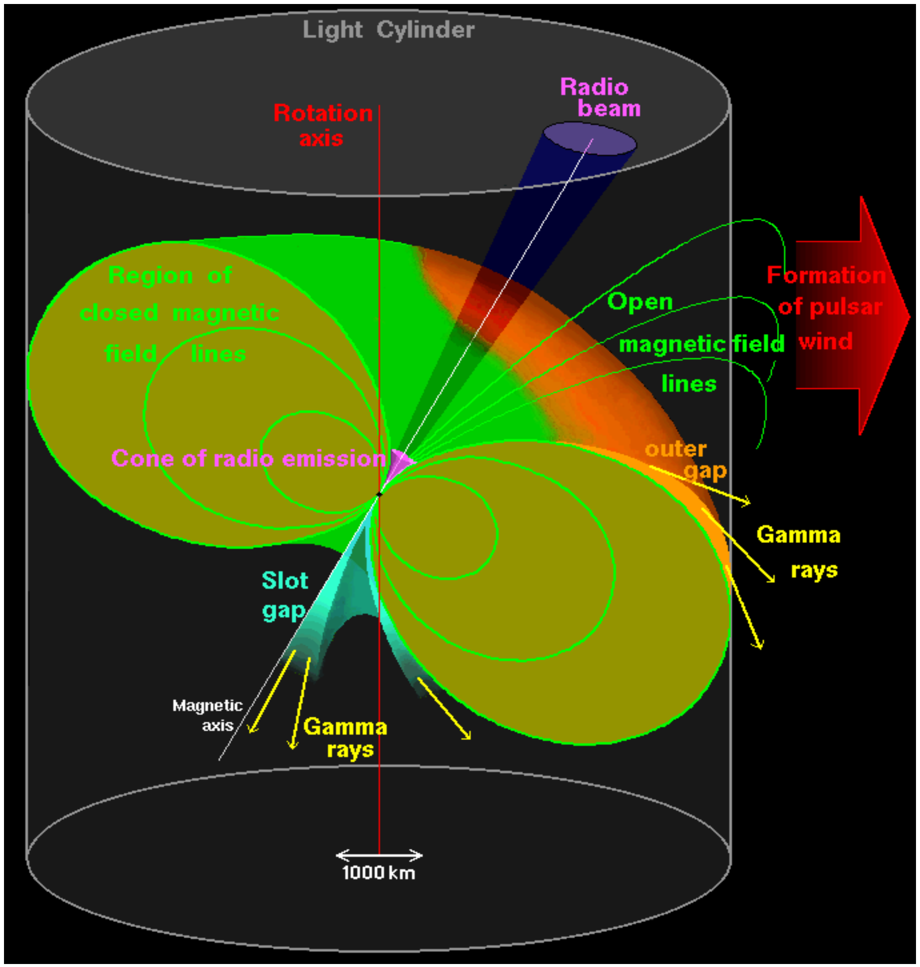
I will talk about XMM-Newton and Chandra observations of **RPPs**

P-Pdot diagram for pulsars



Rotation-Powered Pulsars (RPPs):

Neutron stars (NSs) whose radiation is powered by loss of NS rotation energy (via creation and acceleration of e+e- pairs in strong magnetic field, **B ~ 10^{11} – 10^{13} G**)



(Harding 2009)

Spin-down power

$$\dot{E} = dE_{rot}/dt = 4\pi^2 I \dot{P} P^{-3}$$

$$L = \eta \dot{E}$$

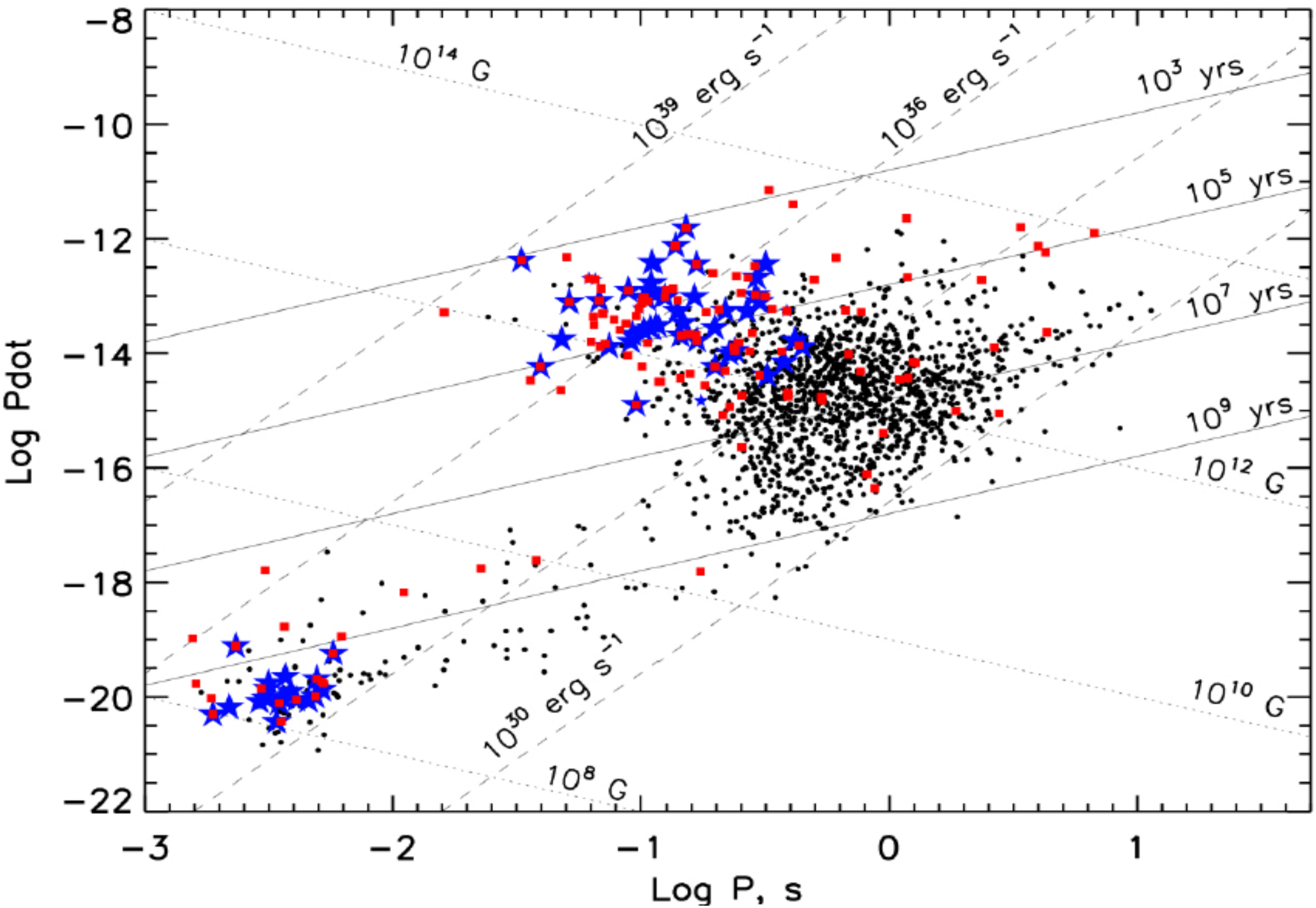
L – luminosity

η – radiative efficiency

Detected RPPs:

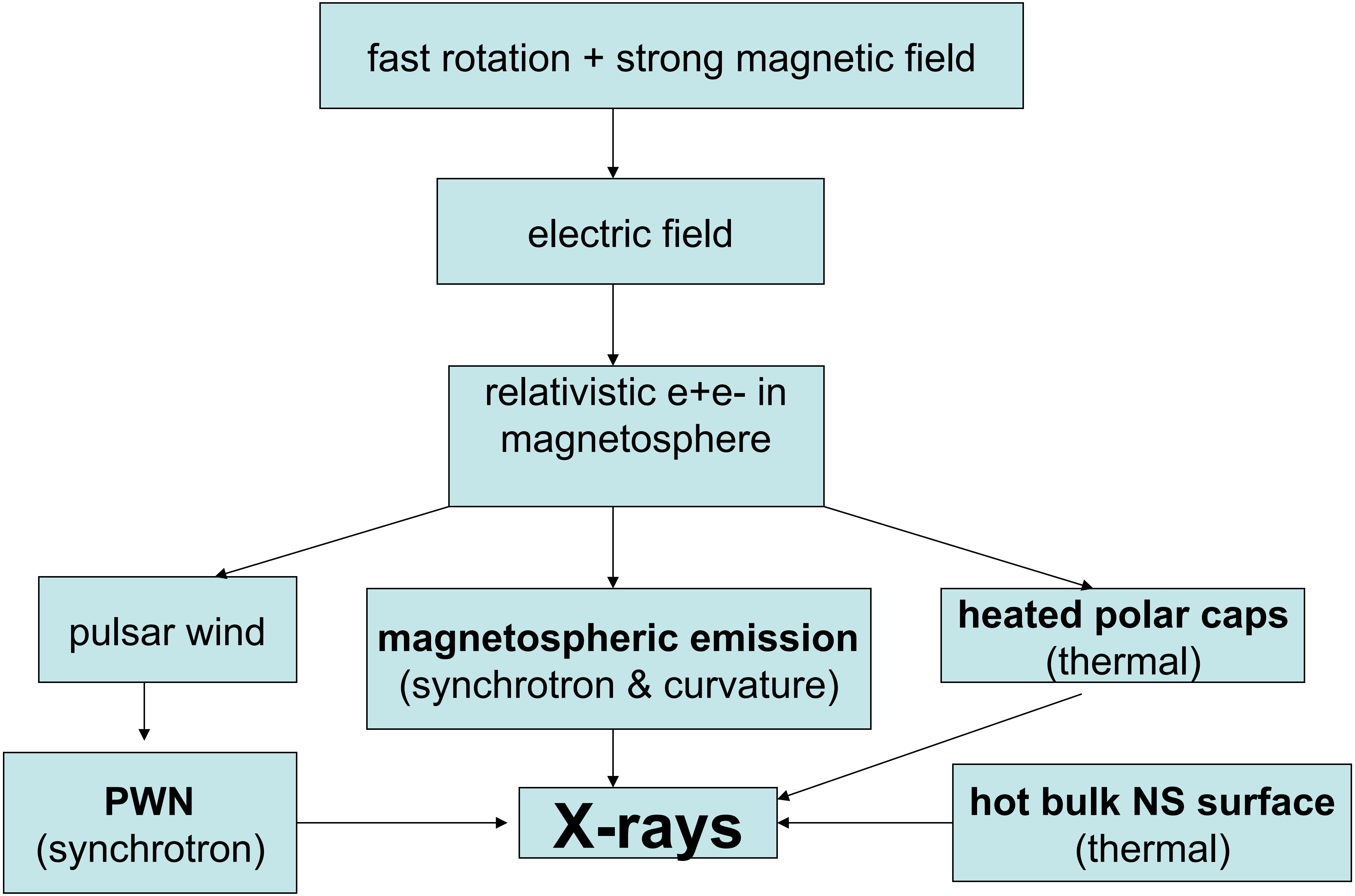
~2000 in radio
~10 in optical (+NIR+UV)
~100 in X-rays
~100 in γ-rays

RPPs detected in X-rays (red dots) and γ-rays (blue stars)



RPPs exist due to constant supply of relativistic e-e+ into magnetosphere.

X-rays from magnetosphere, PWN, and NS surface



X-ray emission components in RPPs:

Nonthermal – seen from radio to gamma-rays

Magnetosphere

PWN (if the PWN is not resolved)

Thermal – seen from UV to soft X-rays

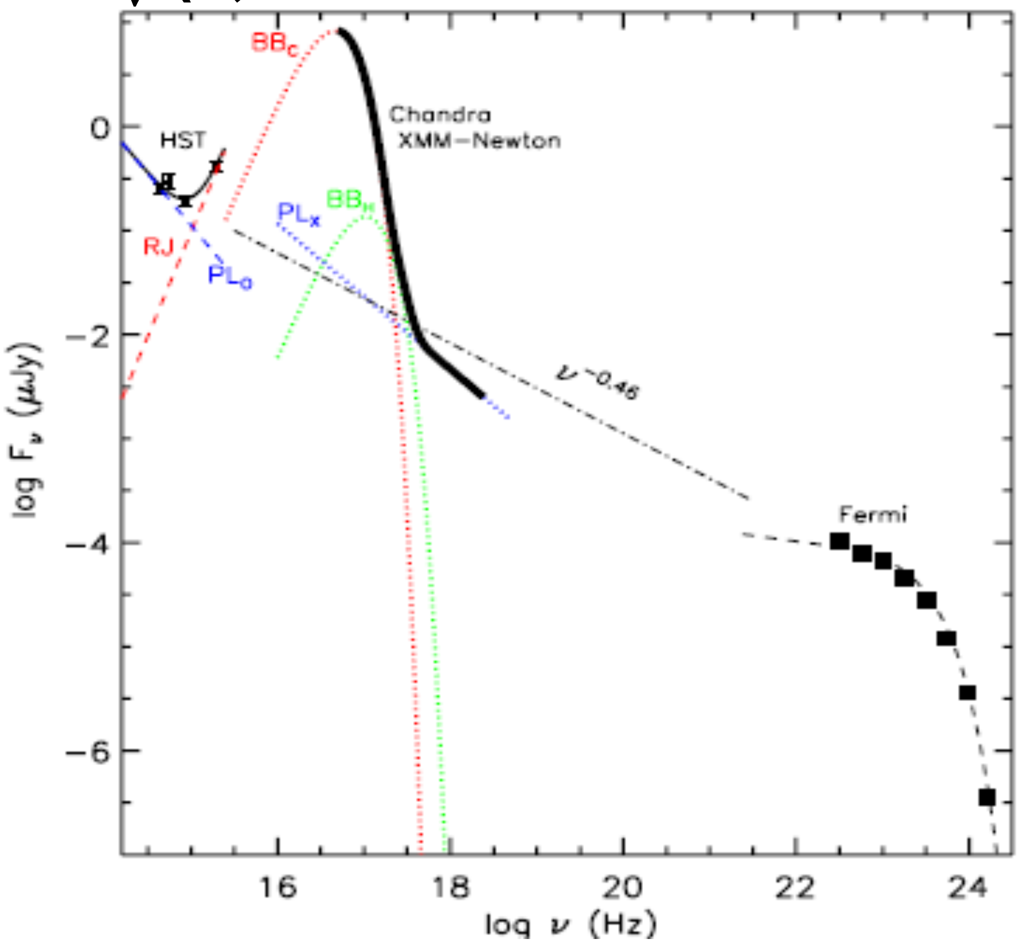
Bulk NS surface (heat is stored/produced inside NS)

Hot polar caps (heated by magnetospheric activity)

Multiwavelength spectra of RPPs

Example: **Spectrum of PSR B1055-52** (τ = 535 kyr, Edot = 3×10^{34} erg/s) **from optical to gamma-rays**

$F_\nu(\nu)$

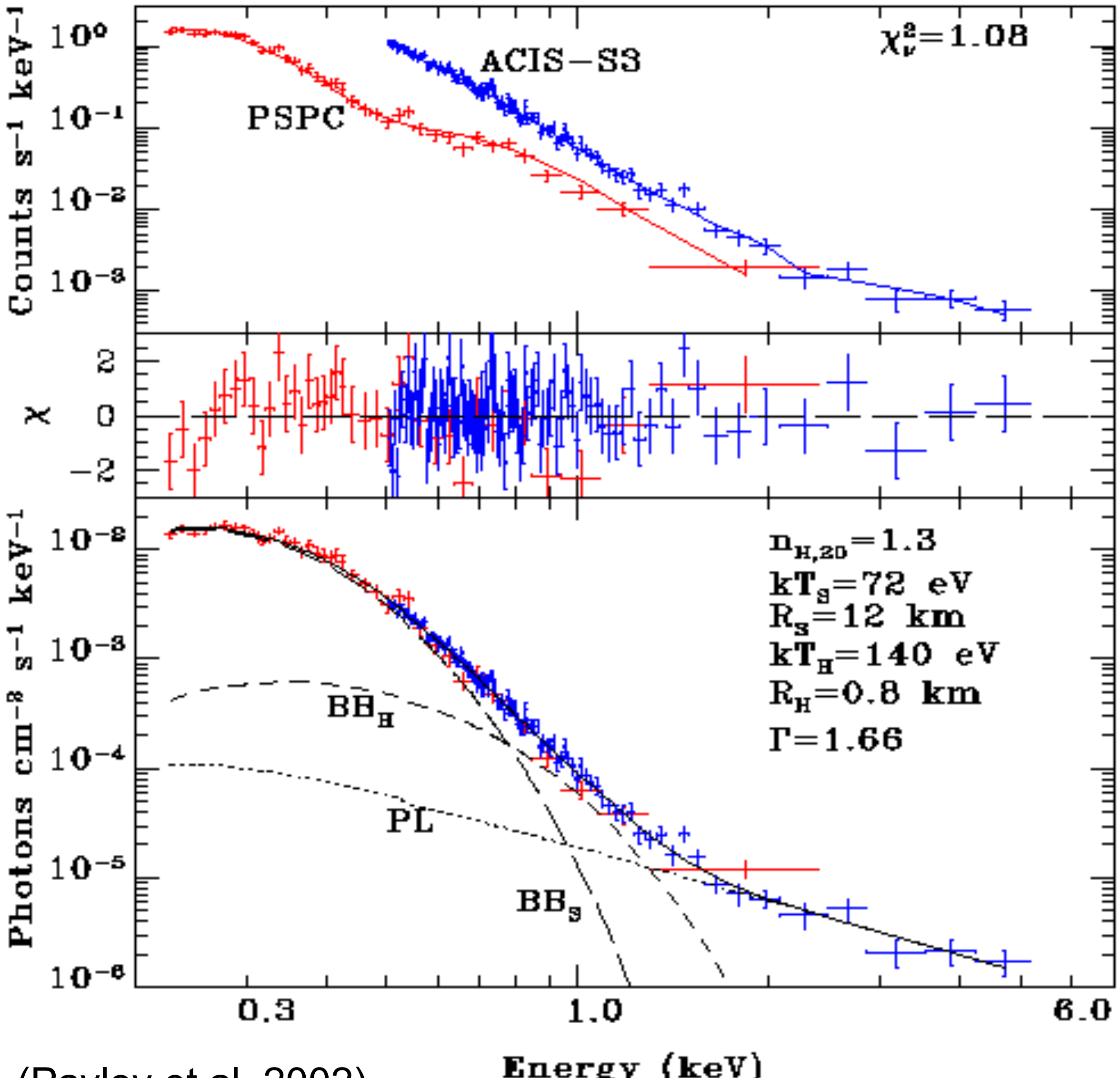


(Mignani, GP, Kargaltsev 2011)

Optical, hard X-rays, γ-rays: **magnetospheric emission** – ~ power law with exp cutoff at GeV energies

UV, soft X-rays: **thermal emission from NS surface** – resembles black-body, seen as a“hump” on the magnetospheric spectrum

Zoom-in on X-ray spectrum of **PSR 1055-52** (Chandra+ROSAT)



(Pavlov et al. 2002)

Two thermal components:

Soft thermal:
72 eV, 12 km

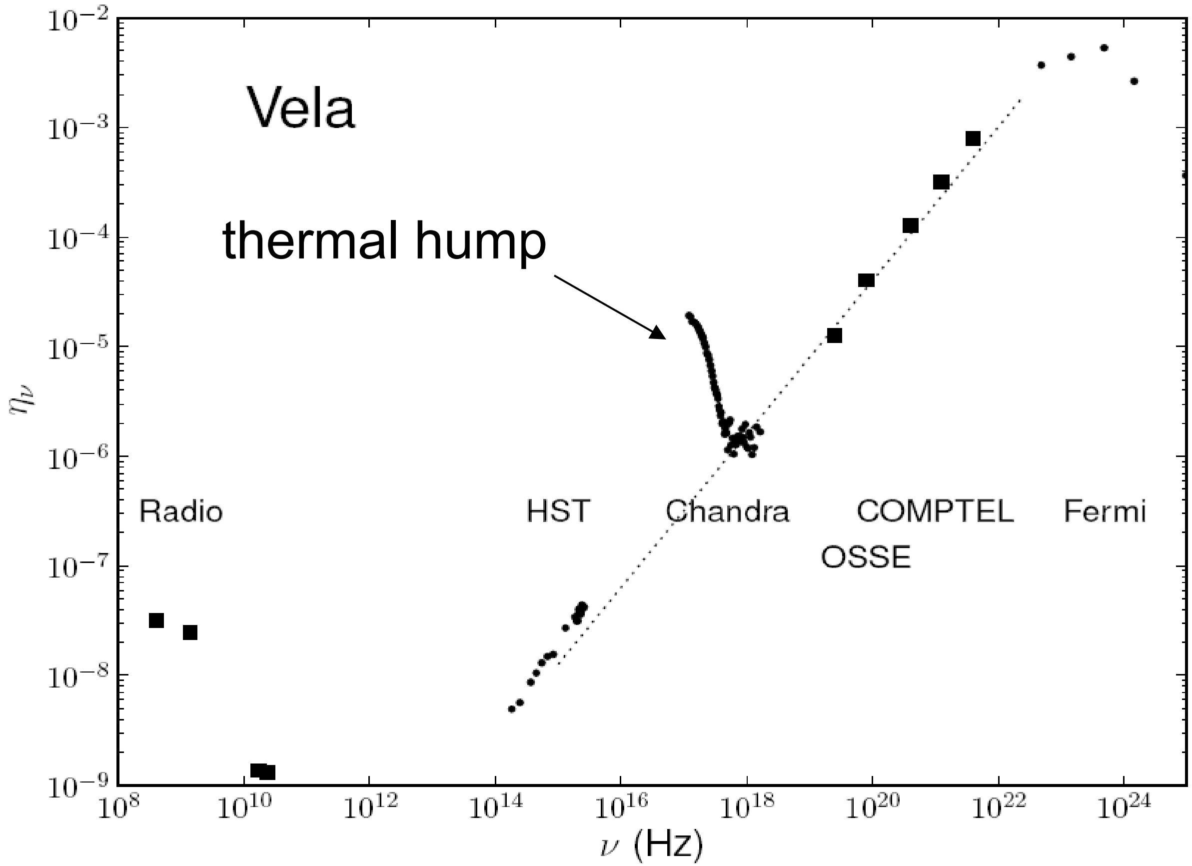
Hard thermal:
140 eV, 0.8 km

Magnetospheric component:

power-law,
photon index
Γ = 1.7

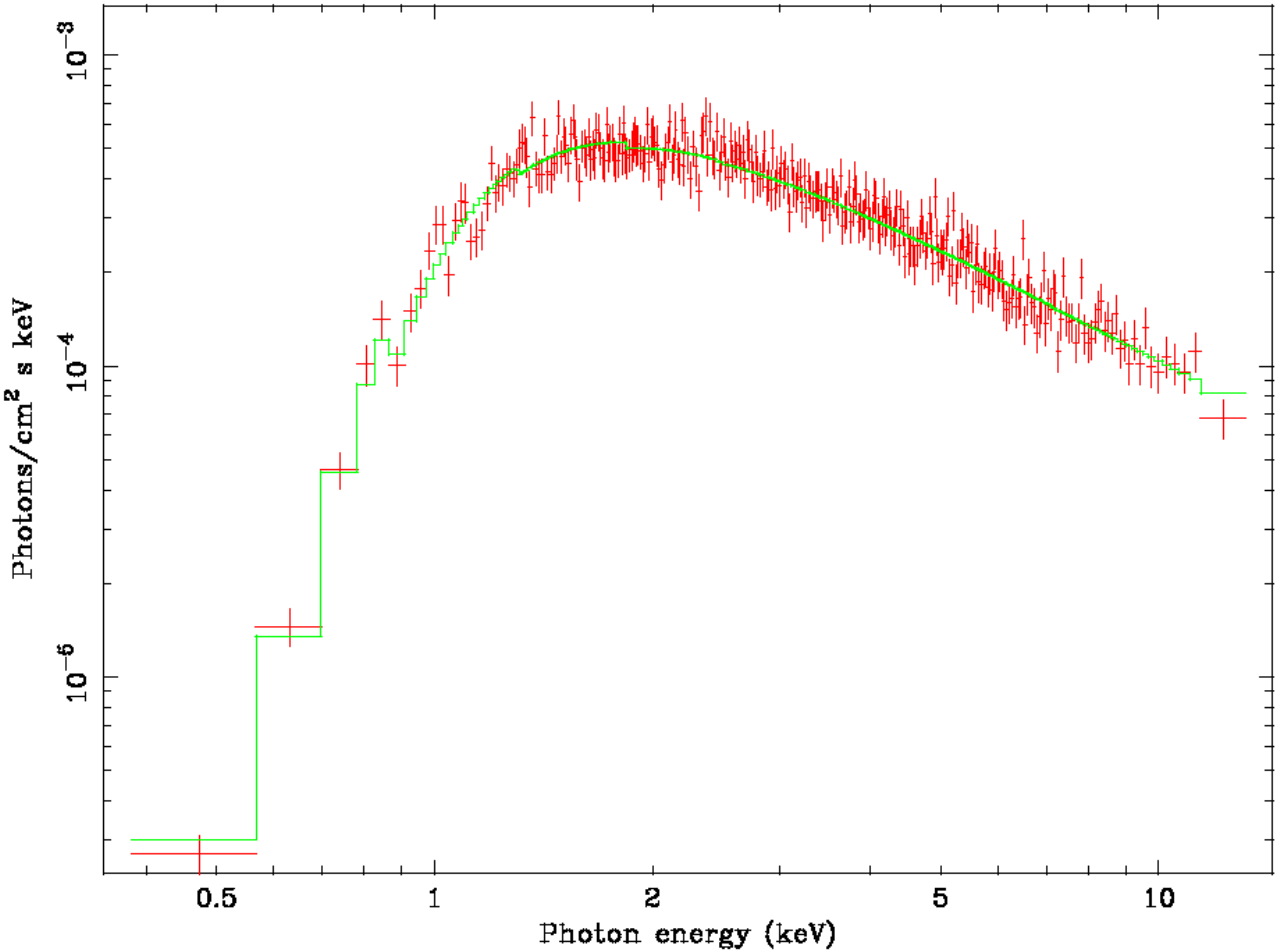
Another example: **Spectral efficiency of the Vela pulsar** (τ = 11 kyr, Edot = 7×10^{36} erg/s) **from radio to gamma-rays**

$\boldsymbol{\eta_\nu = \nu F_\nu 4\pi d^2 / Edot}$ -- "spectral efficiency"



Three main components: coherent **magnetospheri**c (radio), incoherent **magnetospheric** (NIR through gamma-rays), **thermal** from NS surface (FUV – soft X-rays)

In some young RPPs magnetospheric component buries thermal one. Example: XMM spectrum of **PSR B1509-58** (τ = 1600 yrs, Edot = 1.8×10^{37} erg/s)

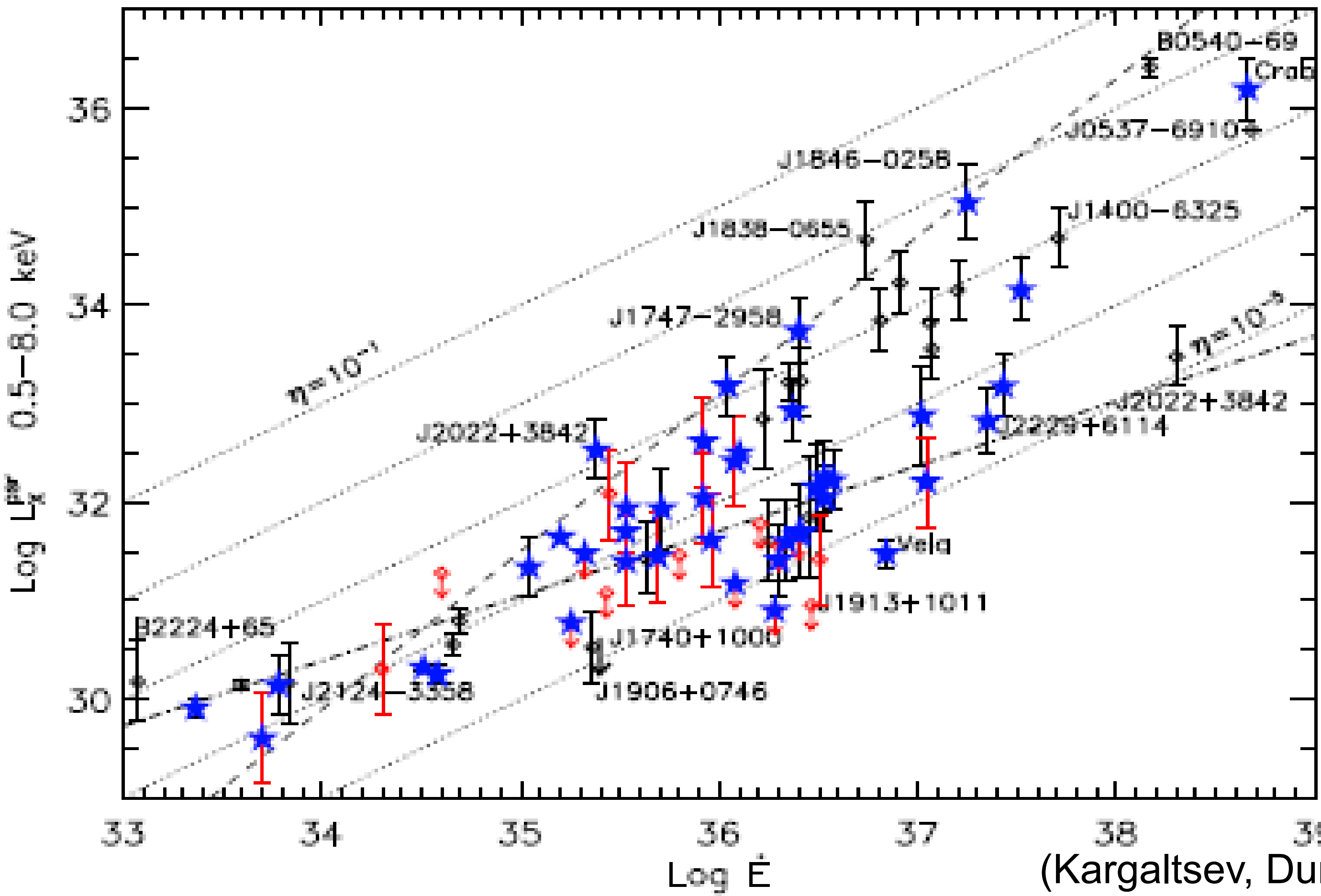


Photon index
Γ = 1.3

Absorbing column
$N_H = 9\times10^{21}$ cm^{-2}

No "thermal hump"

X-ray luminosity and efficiency
of magnetospheric emission vs. Edot

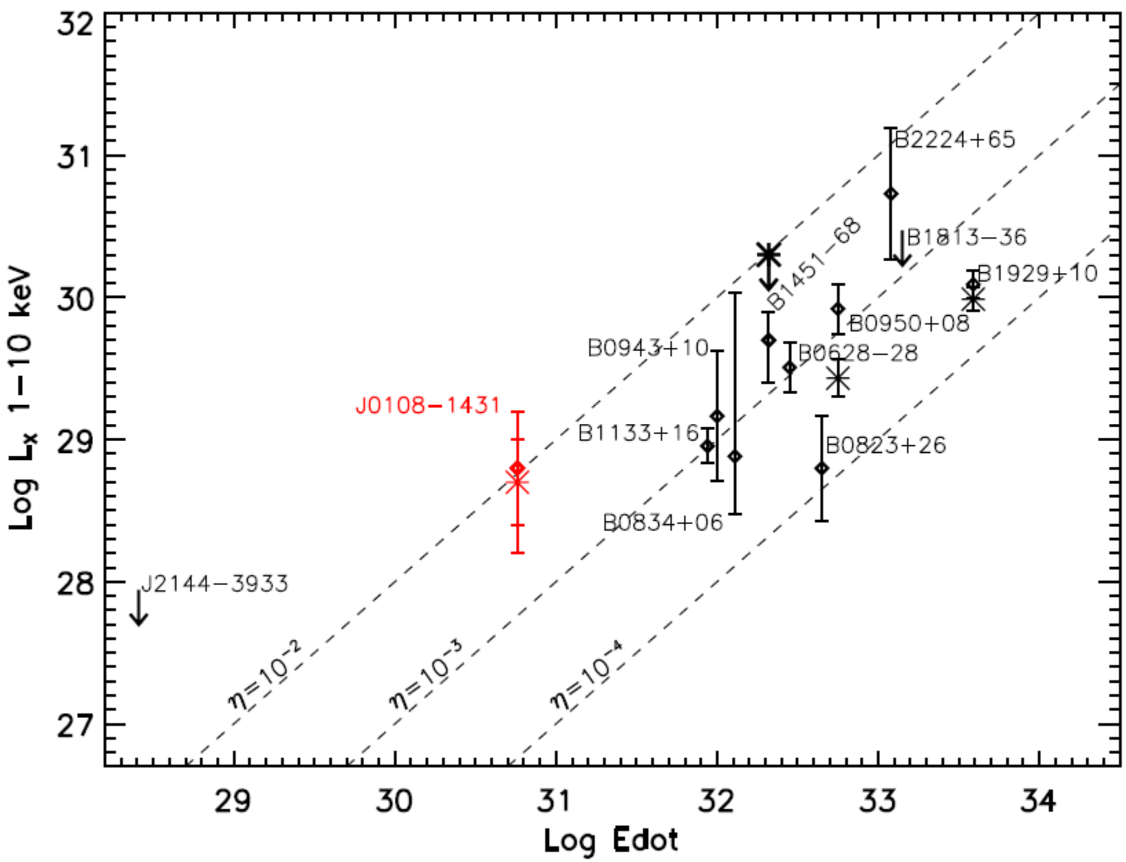


(Kargaltsev, Durant, GP 2012)

L_x generally grows with ***Edot*** (as expected) but ***η_X*** shows a very large scatter, ***η_X* ~ 10^{-6} – 10^{-2}** → ***L_x*** depends not only on ***Edot***

A dozen of **“old” (τ ≥ 1 Myr, Edot ≤ 10^{34} erg/s) RPPs** have been detected recently with Chandra and XMM, including the 170 Myr old **PSR J0108-1431** (Posselt et al. 2012).

X-ray efficiency of old RPPs, $\eta_X \sim 10^{-3} - 10^{-2}$, is higher that in younger ones (~ $10^{-5} - 10^{-3}$).



Possible reasons:

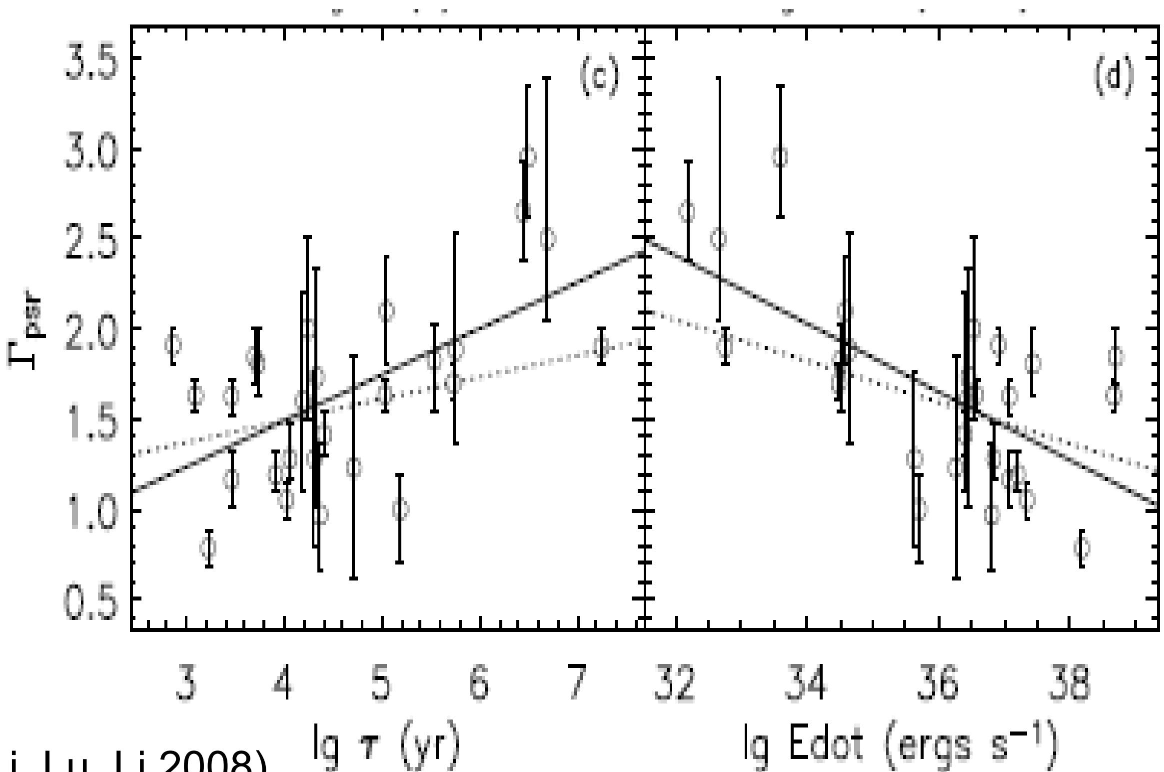
e-e+ are accelerated to lower maximum energies → →maximum of spectral efficiency moves to lower photon energies

Efficiency of polar cap heating grows with decreasing Edot (Harding & Muslimov 2001)

X-ray spectra of RPPs

Magnetospheric component: usually $F_\nu \sim \nu^{-\Gamma+1}$

Slopes (photon indices) $\Gamma \sim 1 - 3$



(Li, Lu, Li 2008)

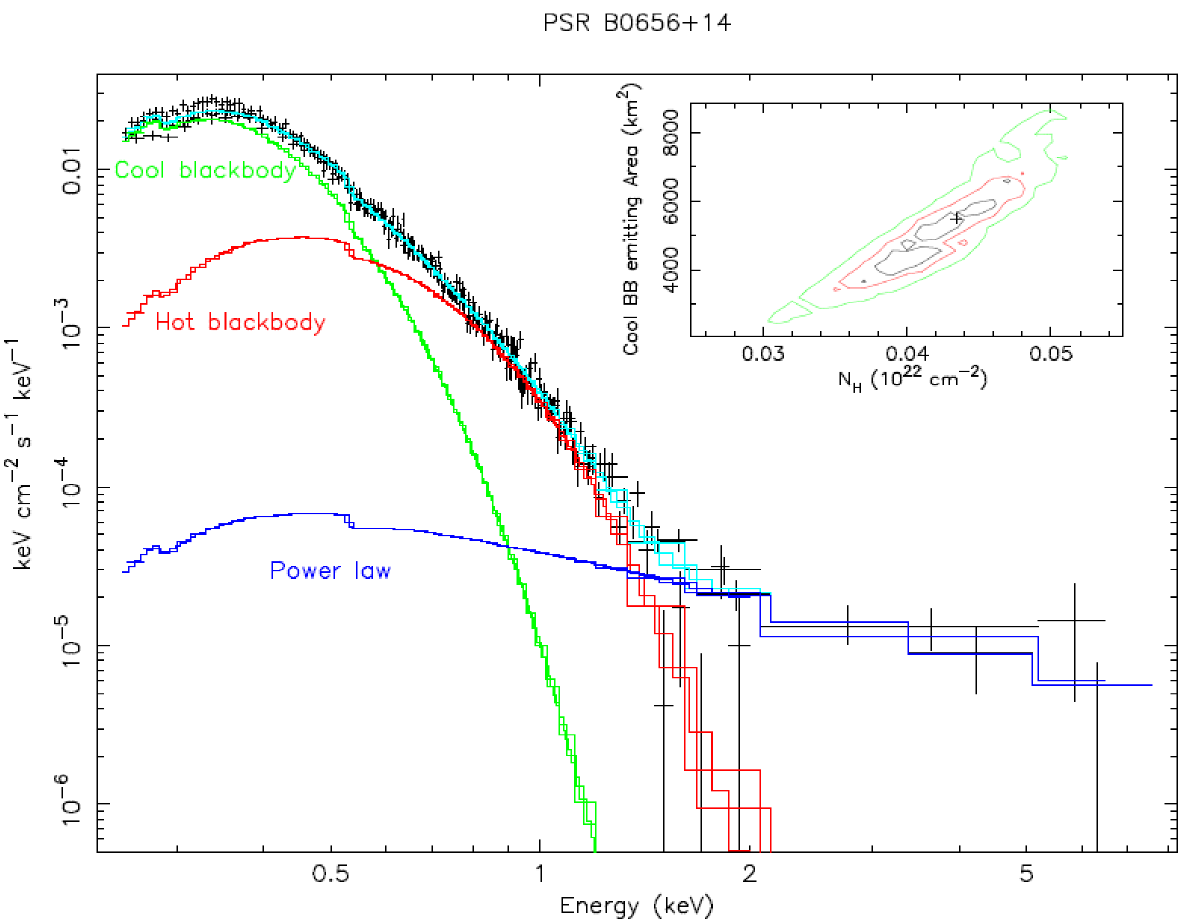
Spectra tend to become steeper (softer) with increasing age (i.e., decreasing Edot)?

However, photon indices may be overestimated for old pulsars (if there is a thermal polar cap component).

Magnetospheric component is **synchrotron radiation** generated by power-law distribution of accelerated electrons ($p = 2\Gamma-1 \sim 1 – 5$) in the "**outer (slot) gap**" ($B \sim 10^6 – 10^8$ G)

Thermal soft (bulk surface) and **thermal hard** (polar cap) components: Usually fitted by **blackbody** spectra.

Example: XMM spectrum of **PSR B0656+14** (τ = 110 kyr, Edot = 3.8×10^{34} erg/s



(De Luca et al. 2005)

kT_S = 55 eV, R_S = 20 km

kT_H = 110 eV, R_H=1.8 km

Γ = 2.1

Typical blackbody temperatures:

kT_S = 30 – 200 eV
(seen up to t ~ 1 Myr)

kT_H ~ 100 – 400 eV
(possibly seen in old RPPs also)

Thermal emission from the bulk of NS surface

Heat is stored (produced) inside the NS.

Residual heat from NS formation: Amount of heat decreases with age (NS cooling via neutrino and photon emission)

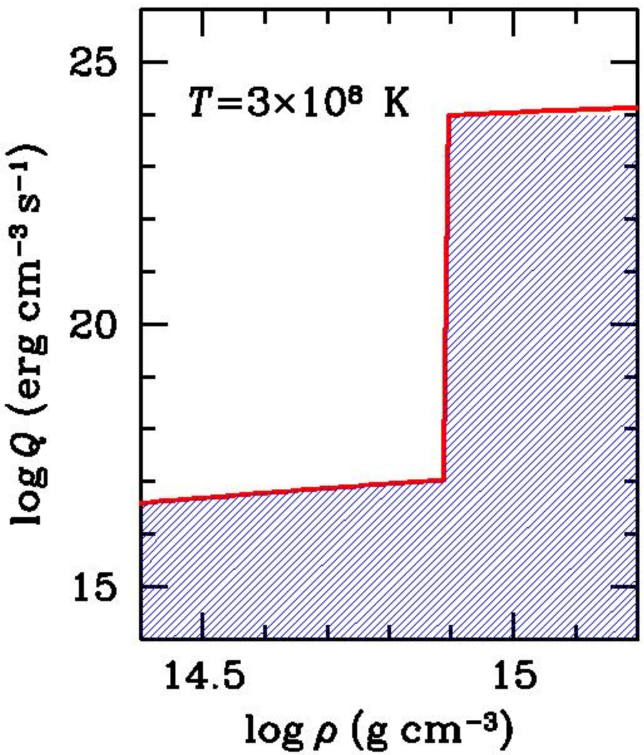
Internal heating (e.g., magnetic field decay, frictional heating, rotochemical heating, etc): Additional heat is supplied throughout NS lifetime.

Is seen from NSs of all types; shifts from X-rays to UV-optical with age; optimal age for X-ray observations: 10 kyr – 1 Myr

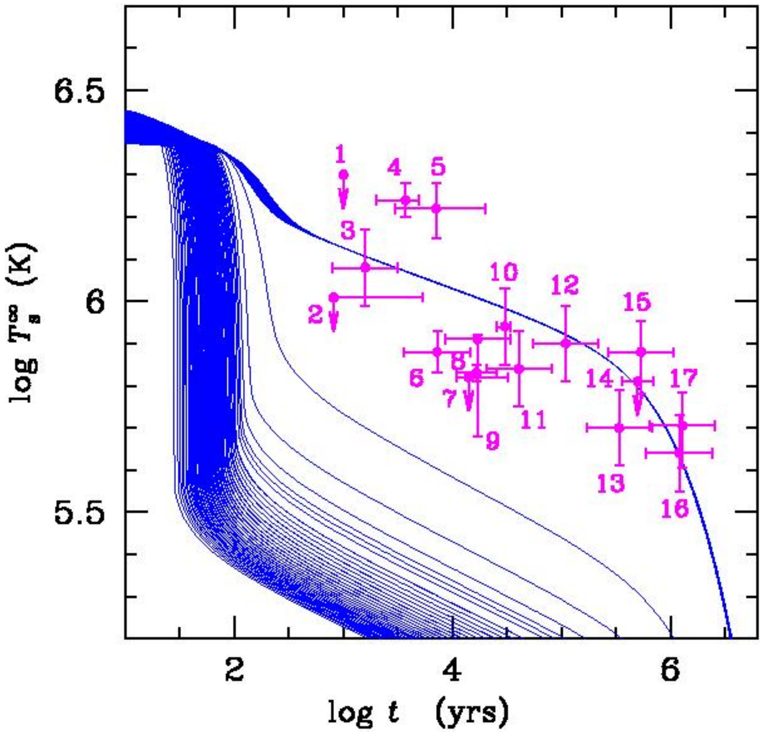
Cooling evolution depends on the properties internal NS matter (equation of state, superfluidity) and NS mass (core density)

1=Crab
2=PSR J0205+6449
3=PSR J1119-6127
4=RX J0822-43
5=1E 1207-52
6=PSR J1357-6429
7=RX J0007.0+7303
8=Vela
9=PSR B1706-44
10=PSR J0538+2817
11=PSR B2234+61
12=PSR 0656+14
13=Geminga
14=RX J1856.4-3754
15=PSR 1055-52
16=PSR J2043+2740
17=PSR J0720.4-3125

ν emissivity vs. density



Temperature vs. age



Modified and direct URCA

$$M_{\mathrm{MAX}} = 1.977\ M_{\mathrm{e}} \qquad \rho_{\mathrm{c}} = 2.578\times10^{15}\ \text{g/cc}$$

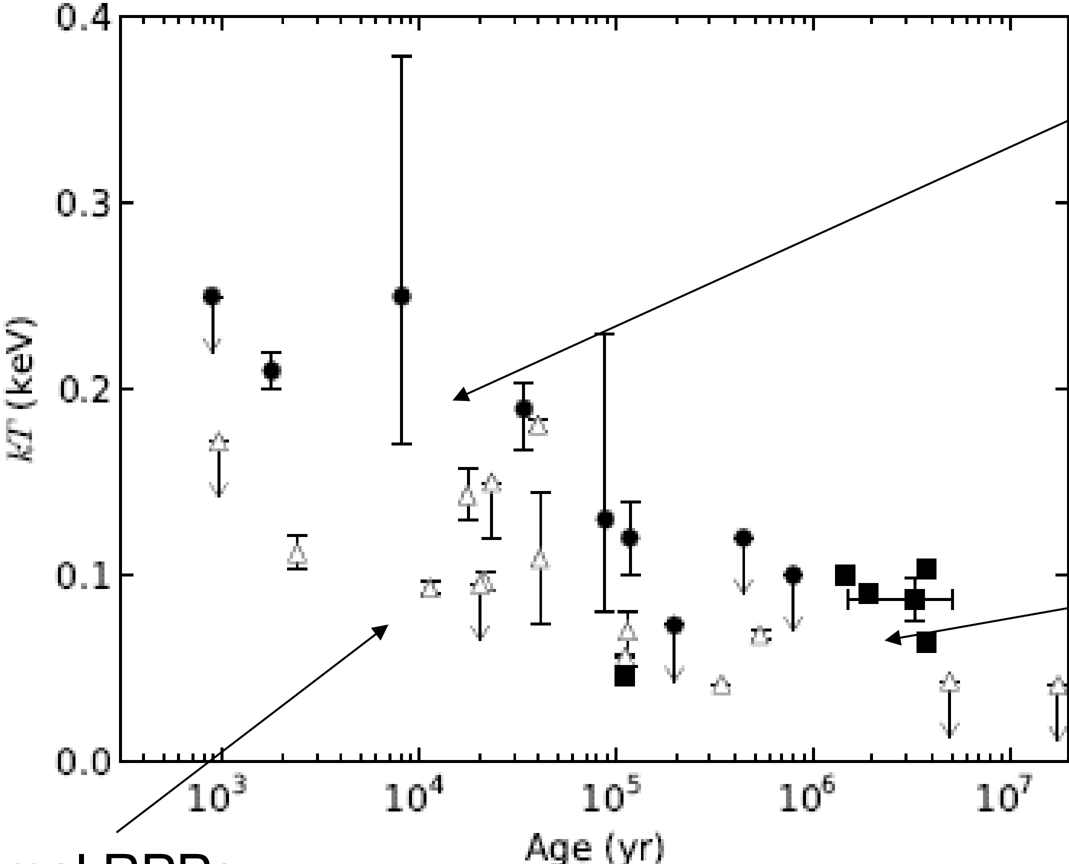
$$M_{\mathrm{D}} = 1.358\ M_{\mathrm{e}} \qquad \rho_{\mathrm{c}} = 8.17\times10^{14}\ \text{g/cc}$$

From 1.1 M_{e} to 1.98 M_{e} with step $\Delta M = 0.01\ M_{\mathrm{e}}$

(Courtesy of D. Yakovlev)

The above cooling models neglect effects of magnetic fields, which may be substantial if B >10^{13-14} G, now or at younger ages.

Indications of **positive correlation between surface temperature and magnetic field** (Pons et al. 2007).



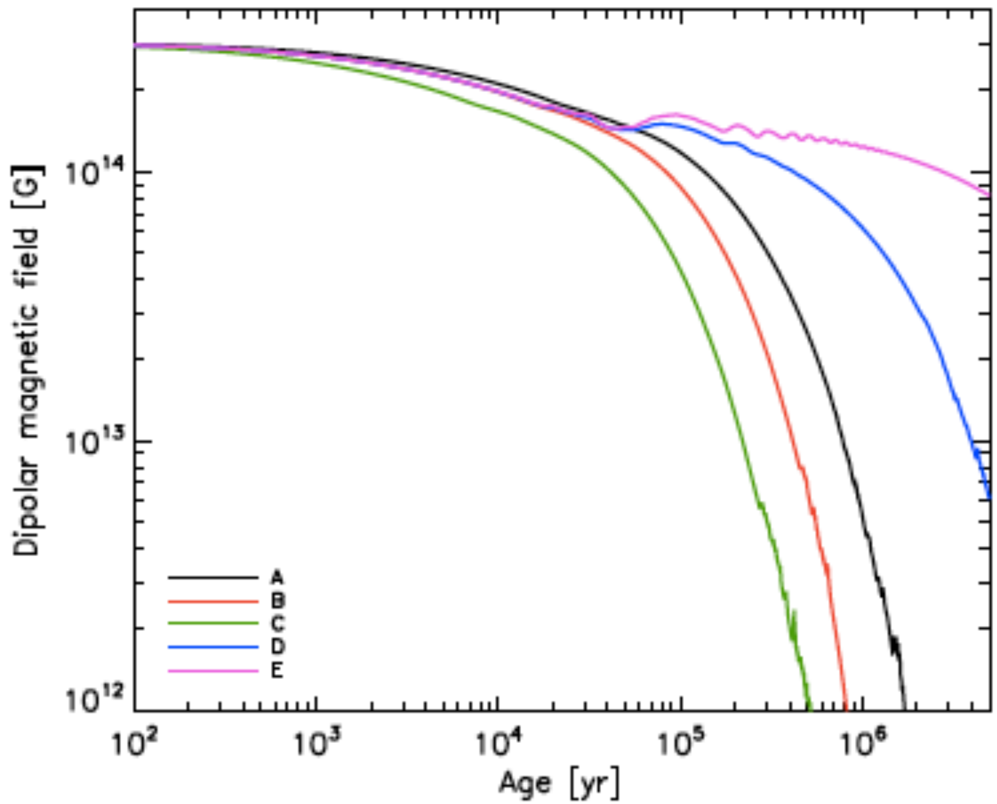
high-B pulsars

TENSs

normal RPPs

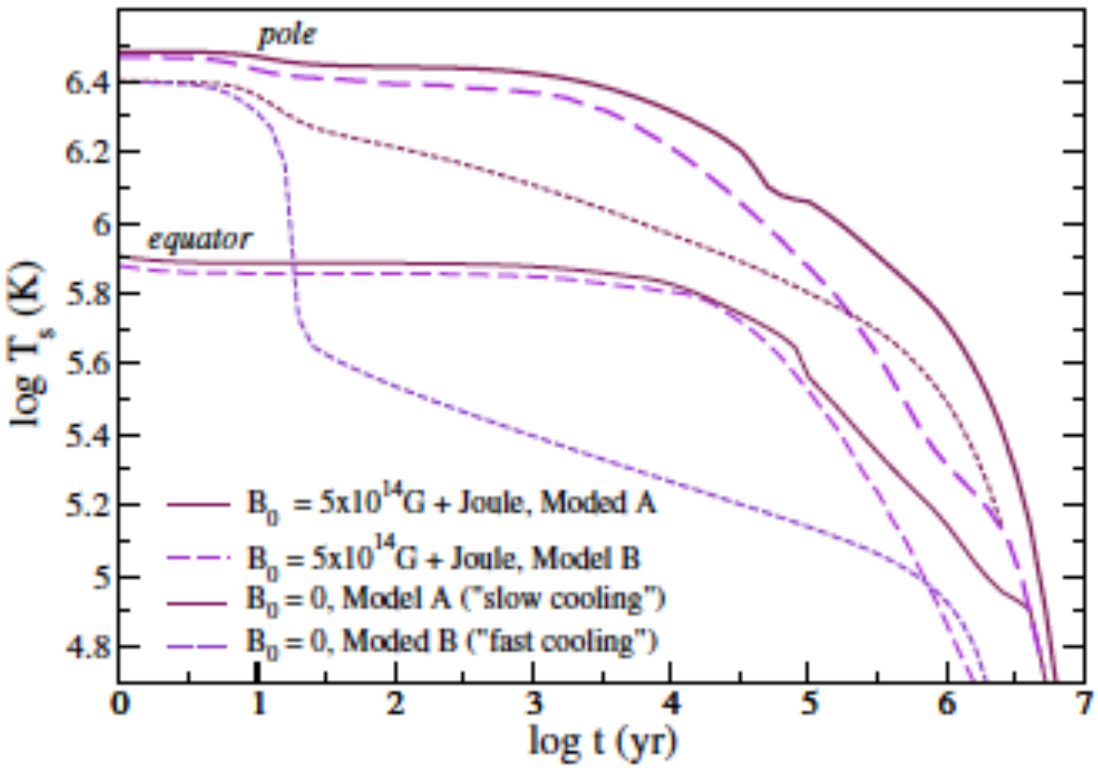
(Zhu et al. 2010)

RPPs could have higher magnetic fields at younger ages due to **magnetothermal evolution** (Aguilera et al. 2008, Pons et al. 2009)



(Pons et al. 2013)

This leads to hotter NS surface due to Joule dissipation, with different temperatures at the magnetic pole and equator



(Aguilera et al. 2008)

(talks by J. Pons and D. Viganò)

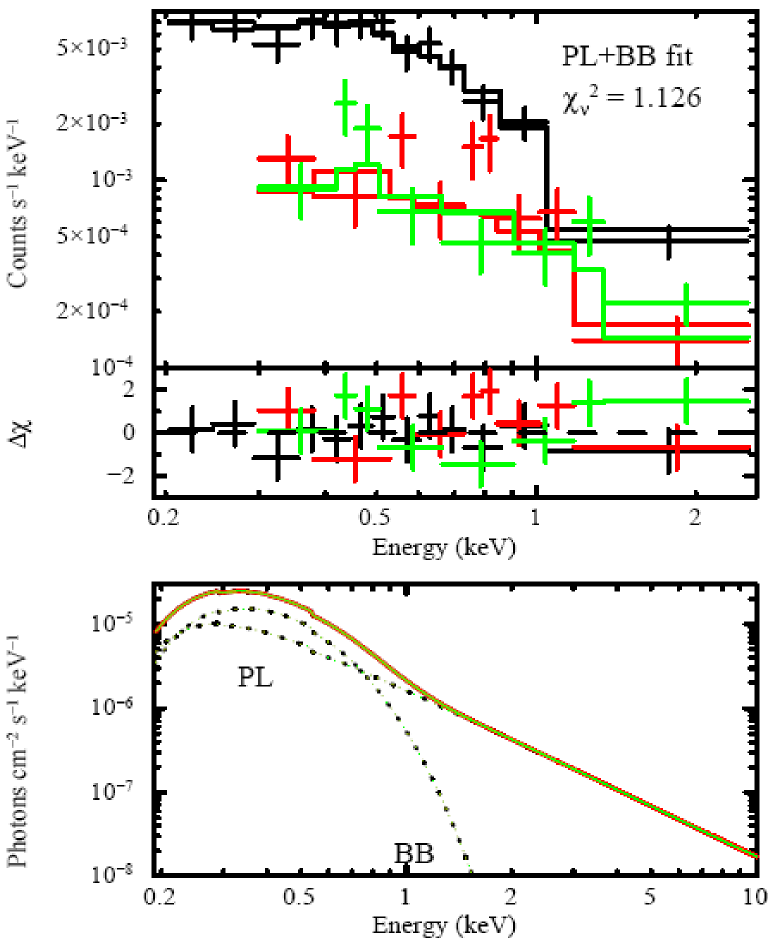
On spectra of old RPPs

Spectra of old pulsars can be fitted by **PL models** with large photon indices, **$\Gamma \sim 3 – 4$**, but such fits usually yield **too high absorbing column N_H** (sometimes higher than the total Galactic N_H).

Reasonable N_H values can be obtained in two-component **PL+BB** fits, indicating that there are **magnetospheric and thermal (polar cap) components.**

Example: **Spectrum of PSR J0108-1431, the oldest nonrecycled RPP detected in X-rays** (Posselt et al 2012)

PL fit: $\Gamma = 3.1$, $N_H = 5.5\times10^{20}$ cm^{-2} (vs. total Galactic $N_H = 2.1\times10^{20}$ cm^{-2})



PL+BB fit:

Γ = 2,
kT = 110 eV, R = 46 m,
$N_H = 2.3\times10^{20}$ cm^{-2}

Note:

True shapes of thermal spectra (hence inferred temperatures and sizes) are not very certain

Reason: Spectra emitted from **atmospheres** or **solid surfaces** differ from the Planck spectra.

For instance, **H or He atmosphere** model fits yield effective temperatures a factor of ~1.5 – 2 lower, and sizes ~3 – 10 times larger than the BB fits (Pavlov et al. 1995; Zavlin et al. 1996).

Therefore, the surface temperatures and NS radii inferred from spectral fits should be used with caution. The **bolometric luminosities** are less sensitive to spectral models, **more certain** if the distance is known with a reasonable accuracy.

RPP pulsations in X-rays

Usually:

Magnetospheric component:
Sharp pulsations, high pulsed fraction, sometimes several peaks

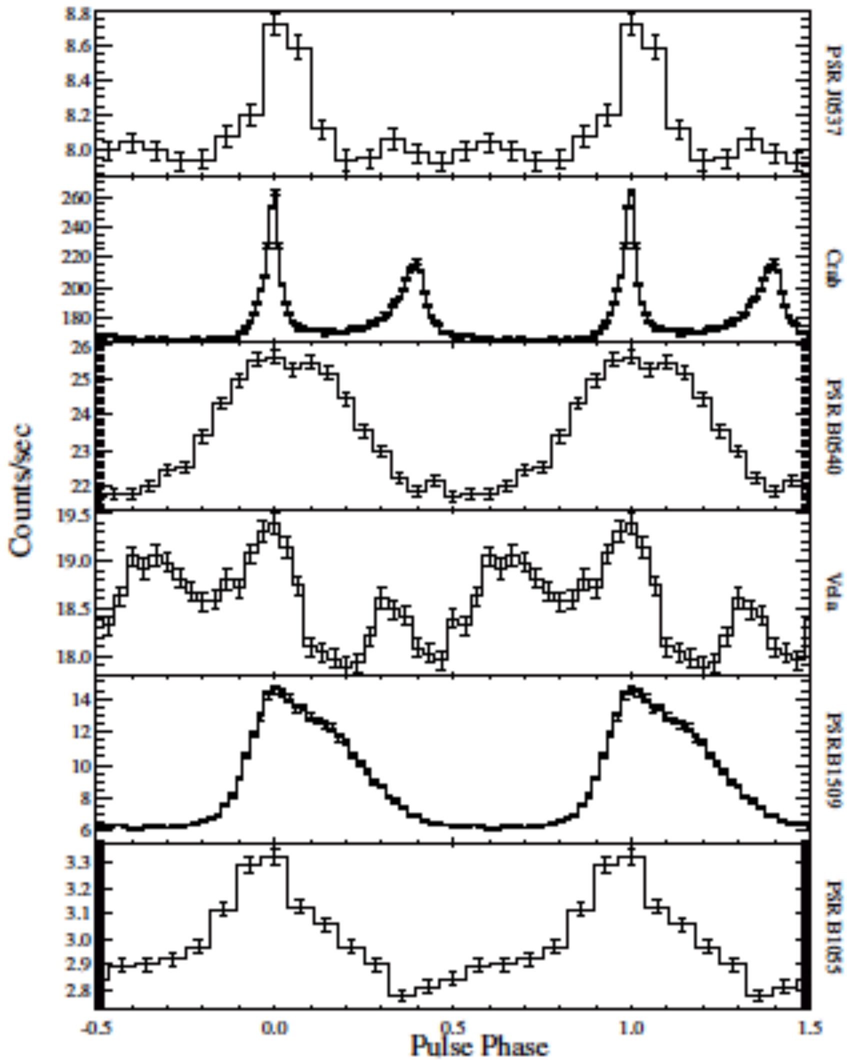
Thermal component(s):
Smooth pulsations, low pulsed fraction

(but there are some exceptions)

Pulse shapes are often asymmetric → lack of axial symmetry in the emission zone

Examples of pulse profiles from XMM observations

0.2 – 12 keV



J0537-69, magnetospheric, 16 ms

Crab, magnetospheric, 33 ms

B0540-69, magnetospheric, 51 ms

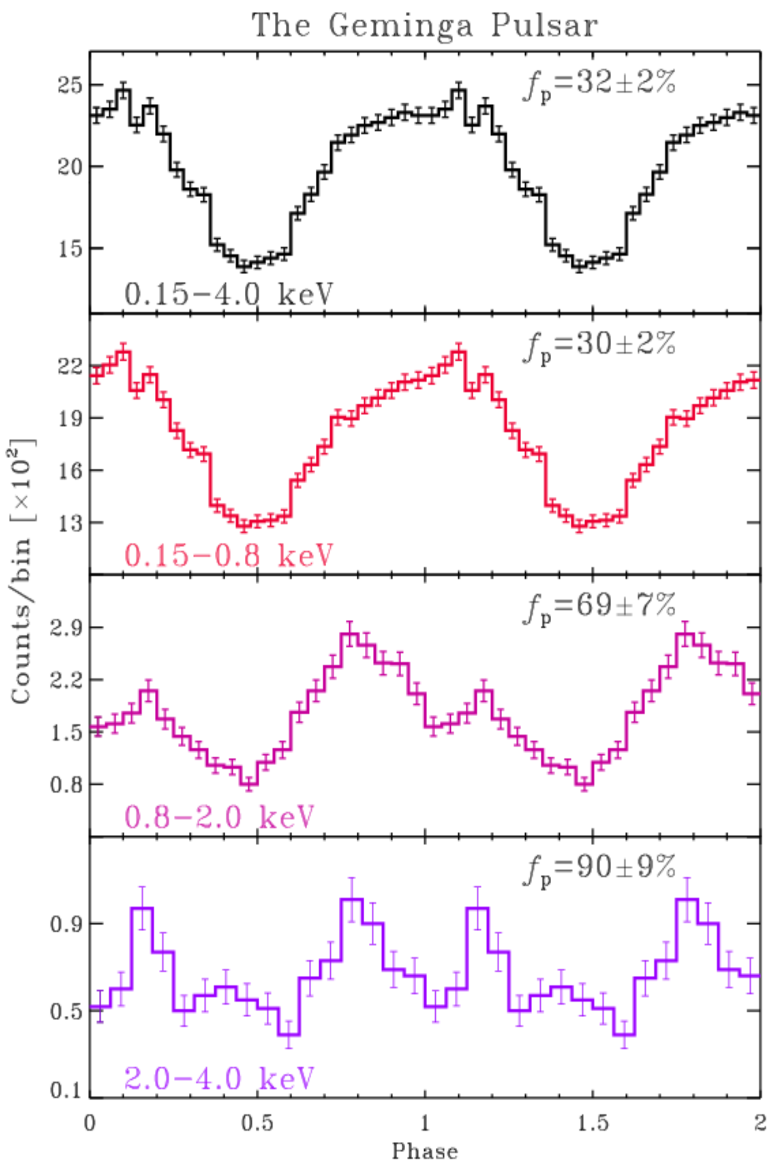
Vela, magnetospheric+thermal, 89 ms

B1509-58, magnetospheric, 151 ms

B0656+14, thermal+magnetospheric, 197 ms

(Martin-Carrillo et al 2012)

Energy-dependent pulsations: Geminga (radio-quiet RPP)



0.15 – 4.0 keV, composite light curve

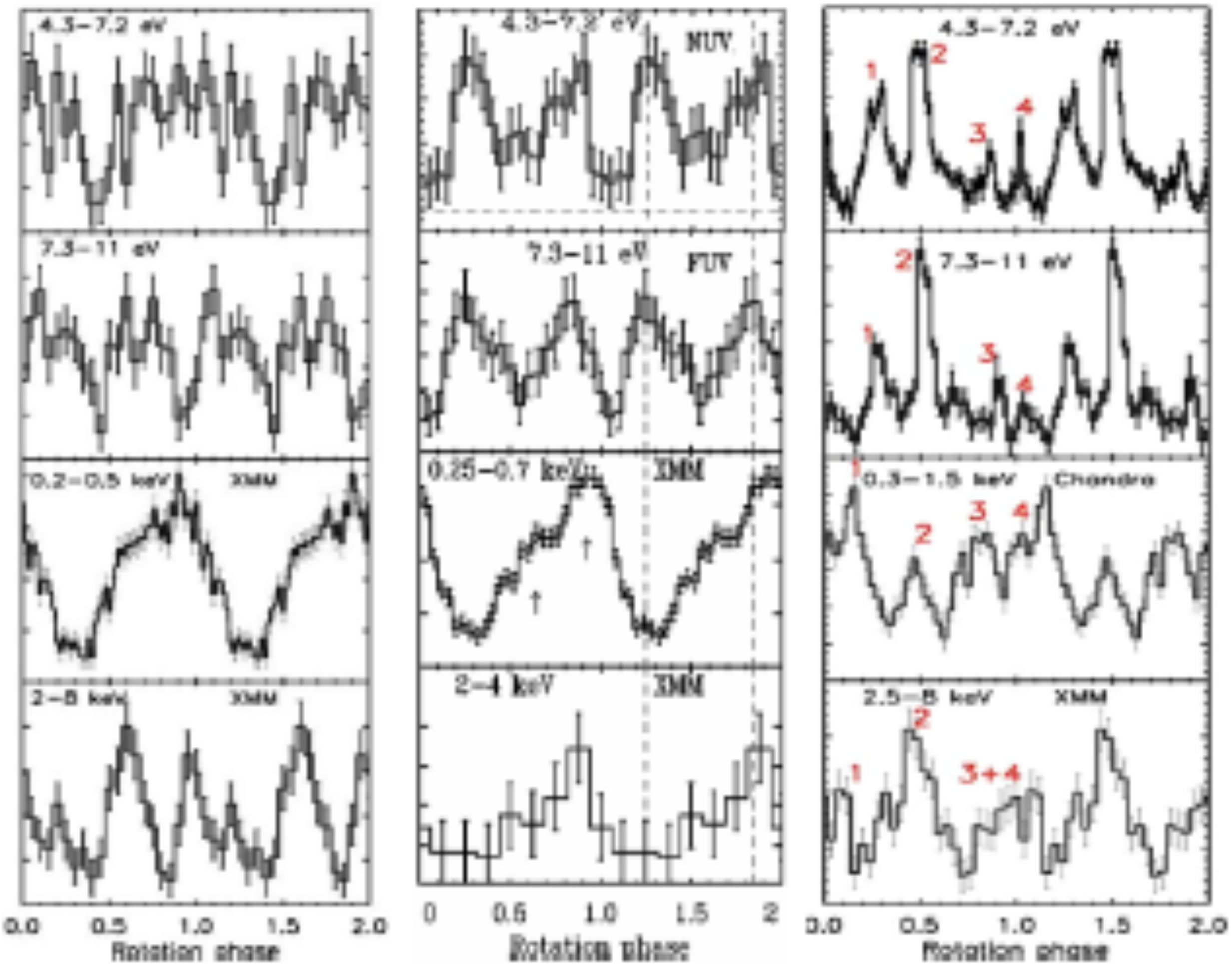
0.15 – 0.8 keV, mostly thermal emission, one broad peak, nonuniform temperature

0.8 – 2.0 keV, magnetospheric emission becomes dominating, two peaks emerge

2.0 – 4.0 keV, purely magnetospheric, two narrow peaks, high pulsed fraction, similar to GeV pulsations

X-ray – UV pulsations

Geminga B0656+14 Vela



NUV, 4.3 – 7.2 eV

FUV, 7.3 – 11 eV

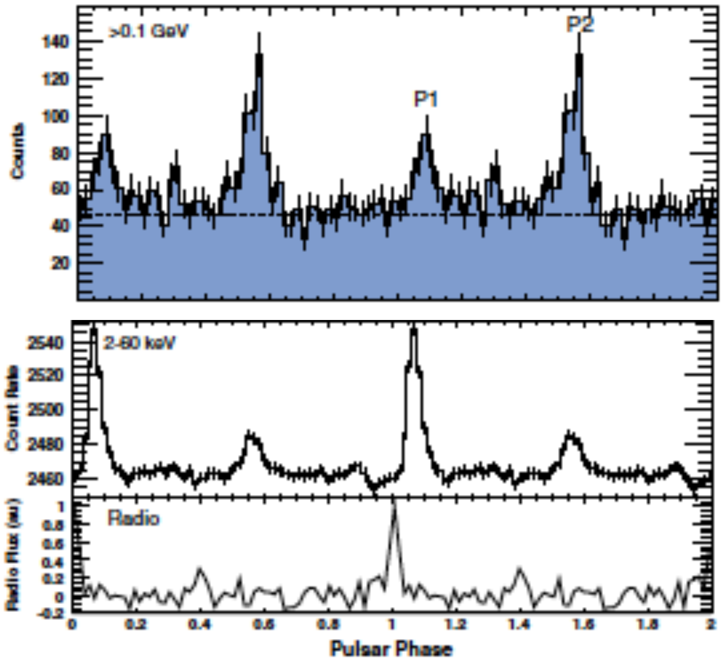
Soft X-rays,
~0.3 – 1 keV

Harder X-rays,
~ 2 – 8 keV

(Kargaltsev, GP 2007)

Gamma-ray – X-ray – radio pulsations

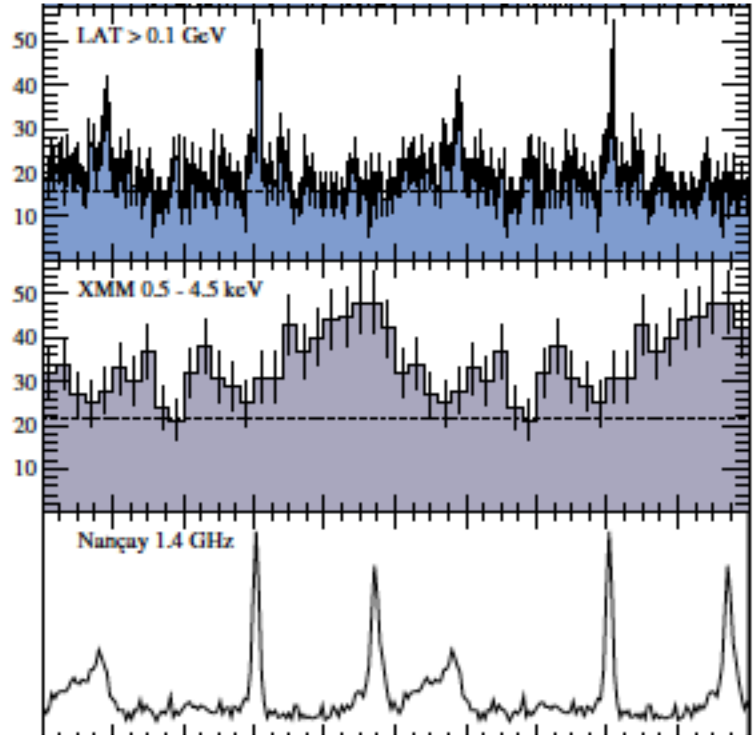
J0205+6449 in 3C 58



(Abdo et al. 2009)

γ-ray peaks coincide with X-ray peaks, different relative heights; radio peak slightly shifted

Black widow B1957+20



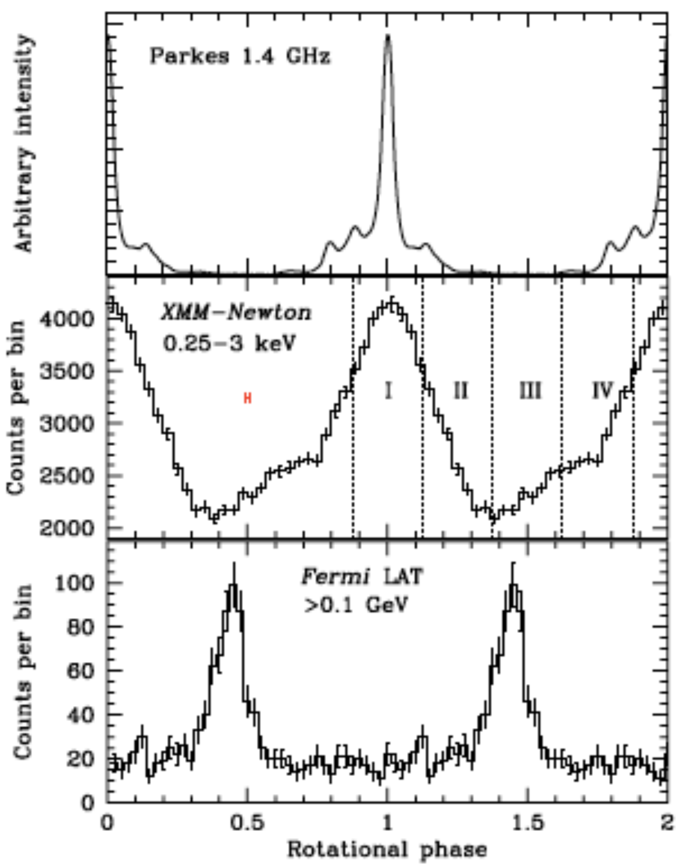
(Guillemot et al. 2011)

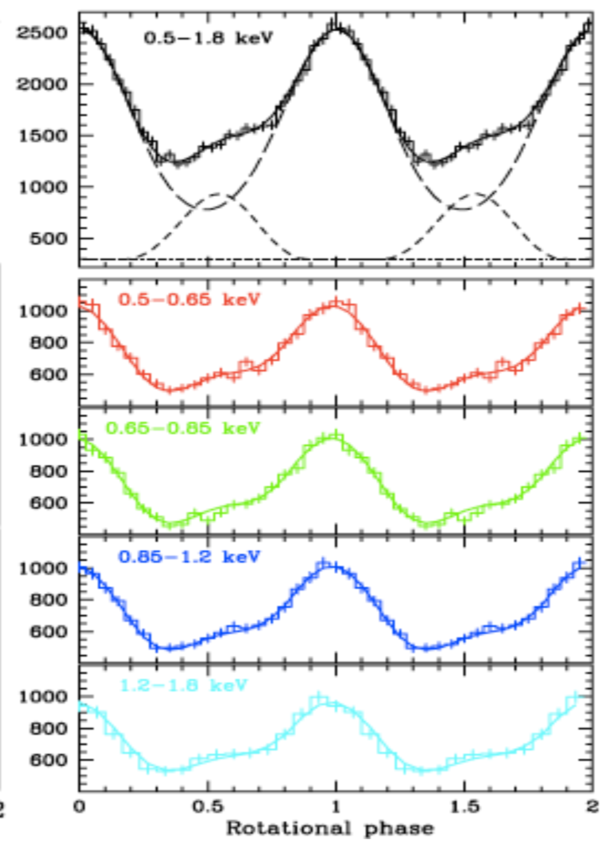
Main γ-ray and radio peaks coincide , misaligned with X-ray peak(s)

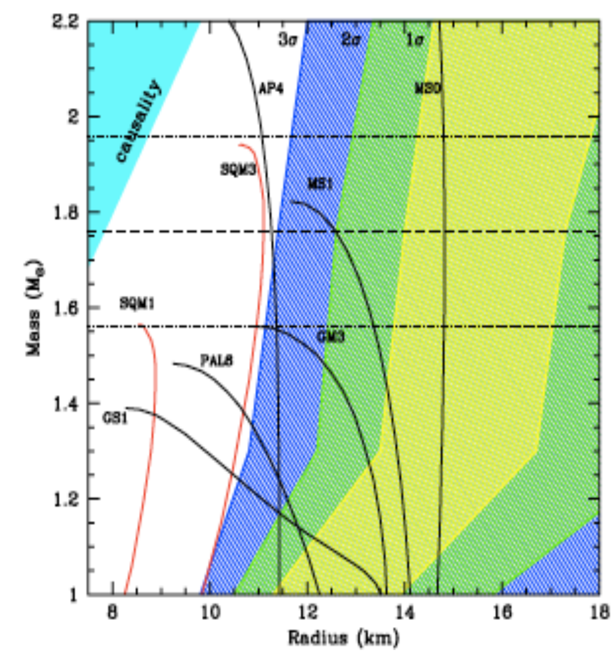
Pulse shape of thermal emission from polar caps depends on M/R (bending photon trajectories)

(Pavlov, Zavlin 1997, 1998; Bogdanov et al. 2007)

This effect was used to constrain R for the nearest recycled pulsar J0437-4715 (most recently by Bogdanov 2013 from XMM data).







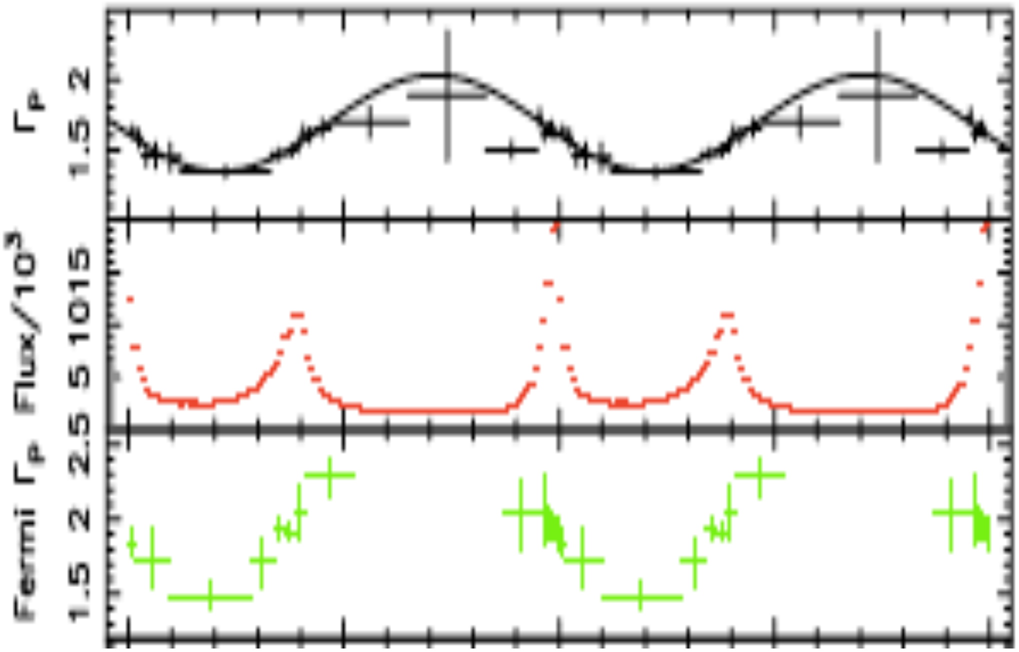
M≅1.76 M_{sun} (radio timing)

R > 11.1 km (3 σ)

hard EOS

Spectral parameters depend on pulsation phase

Example: Crab pulsar



X-ray photon index varies from 1.3 to ~1.8

softer at pulse peaks than in the pulse-interpulse bridge

in concert with γ-ray photon index

(Weisskopf et al. 2011)

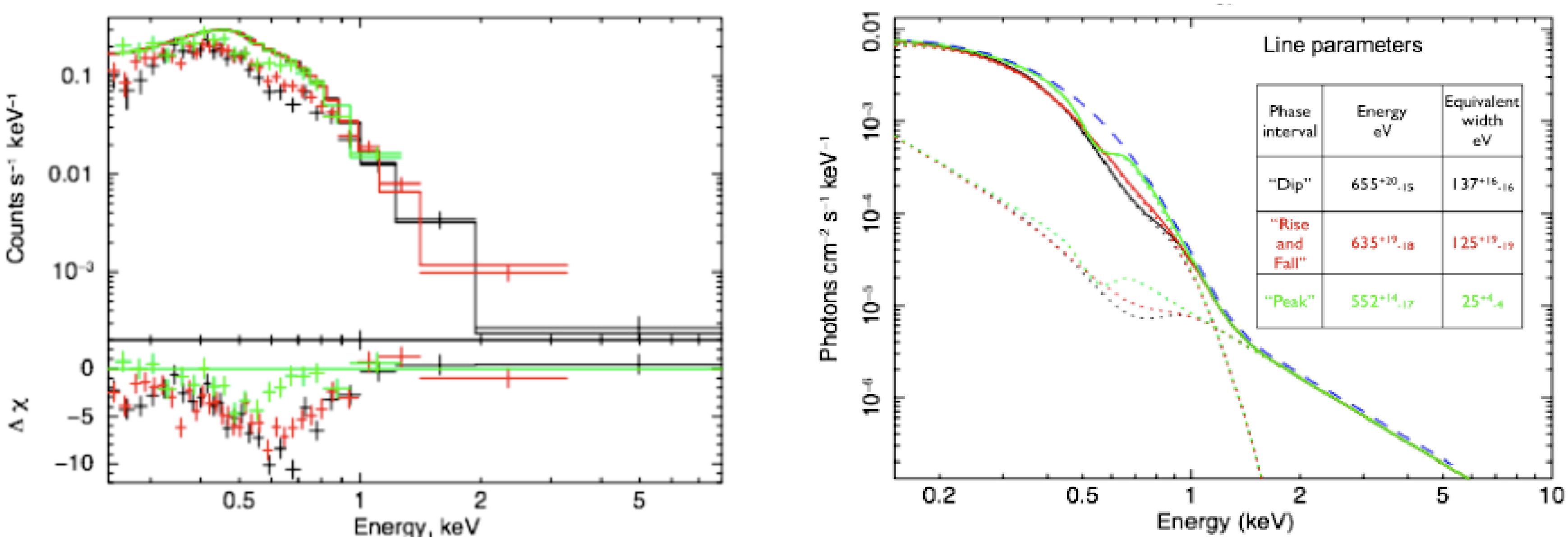
There are large variations in the pair spectrum along the magnetosphere region (slot gap?) where the radiation is generated

Some RPPs show **phase-dependent absorption features**

Example: XMM data on **PSR J1740+1000**

(Edot = 2.3×10^{35} erg/s, τ = 23 kyr, B=1.8×10^{12} G)

Spectra at three phase intervals (Kargaltsev et al. 2012)



Broad absorption feature(s) @ **0.5-0.6 keV** and perhaps **0.2-0.3 keV**

Central energy and depth vary with rotation phase

Cyclotron absorption in "radiation belts" (closed magnetic field line zone), @ B ~ 5×10^{10} G?

Absorption by "metals" in the NS atmosphere??

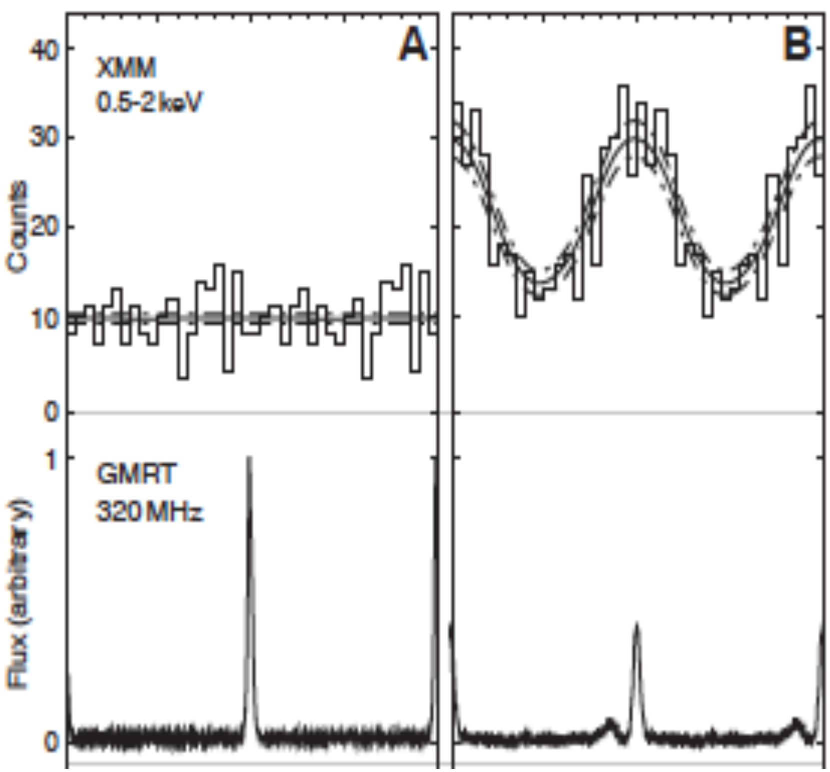
Interesting new development:

Different X-ray properties in different radio pulsar modes

(Hermsen et al. 2013)

PSR B0943+10 (P=1.1 s, τ = 5 Myr) – two modes: Radio bright (**B**) with drifting subpulses, and quieter (**Q**) chaotic mode.

B mode Q mode



B mode: No X-ray pulsations, PL spectrum, Γ = 2.3

Q mode: Strong pulsations, BB spectrum of pulsed component, kT = 0.3 keV

Talk by W. Hermsen

Conclusions

Magnetospheric emission:

- Likely produced in open/slot gaps
- Large scatter of X-ray efficiency → L_X depends not only on Edot
- Spectral slope varies with phase
- Very diverse pulse profiles
- Systematic comparison with γ-ray/UV data and models required

Polar cap thermal emission:

- Surprisingly small sizes
- No clear correlation of temperature with age
- Efficiency grows with age?
- Transient polar caps in some pulsars

Bulk surface thermal emission:

- Nonuniform temperature distribution – due to nonuniform magnetic field?
- Magnetic field decay in NS crust is important heating source
- Broad absorption features of unknown nature