X-ray Isolated Neutron Stars: The Challenge of Simplicity

The Magnificent Seven

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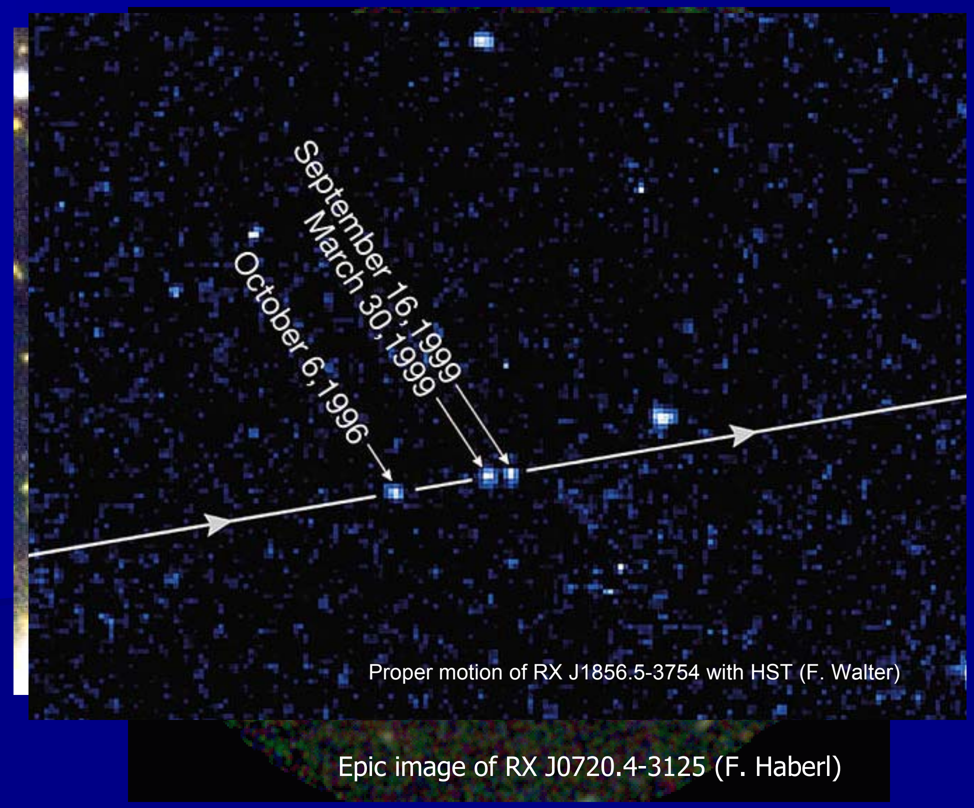


The Seven X-ray Dim Isolated Neutron stars (XDINSs)

- Soft thermal spectrum (kT $\approx$ 50 ...
- ...
- ...on-thermal ...
- ...n density (N ... $^{-2}$)
- ...ations in 5 s... 3-10 s)
- Very faint optical counterparts

Dim ? They are not dim at all !

Right ! What else ? XINSs ? ICONSs ? THEINS ? RINSs ?

More in F. Haberl's talk

Source	kT (eV)	P (s)	Amplitude/2	Optical
RX J1856.5-3754	60	-	< 1%	V = 25.6
RX J0720.4-3125 (*)	85	8.39	11%	B = 26.6
RX J0806.4-4123	96	11.37	6%	-
RX J0420.0-5022	45	3.45	13%	B = 26.6 ?
RX J1308.6+2127 (RBS 1223)	86	10.31	18%	m_{50CCD} = 28.6
RX J1605.3+3249 (RBS 1556)	96	-	-	m_{50CCD} = 26.8
1RXS J214303.7+065419 (RBS 1774)	104	9.43	4%	-

(*) variable source

Featureless ? No Thanks !

- RX J1865.5-3754 is convincingly featureless and non-pulsating (Drake et al. 2002; Burwitz et al. 2003)
- A broad absorption feature detected in all the pulsating XDINSs (Haberl et al. 2003, 2004, 2004a; Van Kerkwijk et al. 2004; Zane et al. 2005)
- E_{line} ~ 300-700 eV
- Proton cyclotron lines ? Atomic transitions at high B ?

$B \sim 10^{13}$ - 10^{14} G

XDINSs: The Perfect Neutron Stars

XDINSs are key in neutron star astrophysics: these are the only sources for which we have a “clean view” of the star surface

- Information on the thermal and magnetic surface distributions
- Estimate of the star radius (and mass ?)
- Direct constraints on the EOS

Simple Thermal Emitters ?

Recent detailed observations of XDINSs require sophisticated modeling to be exploited at full extent

"CONVENTIONAL MODEL" thermal emission from the surface of a neutron star with a dipolar magnetic field and covered by an atmosphere

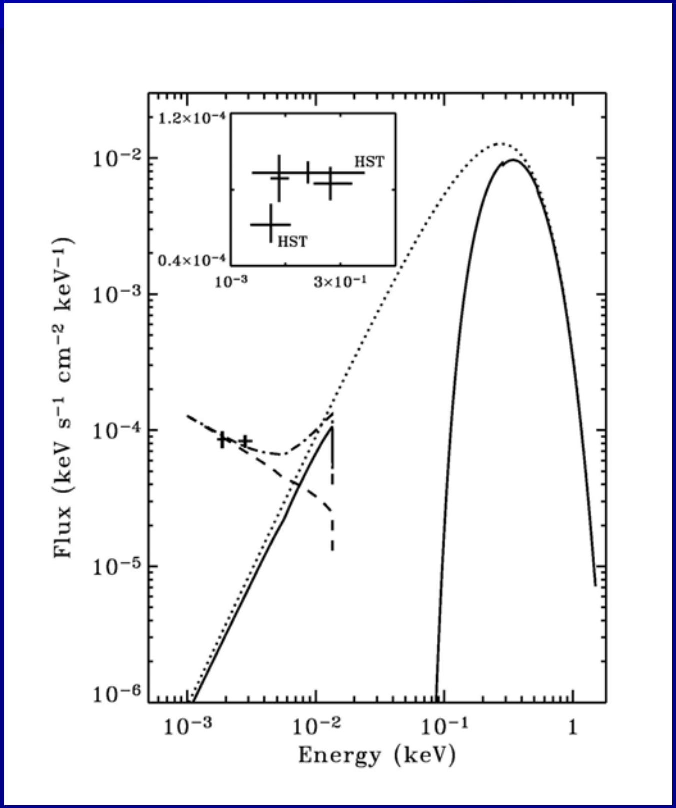
The optical excess

The puzzle of RX J1856.5-3754

XDINS lightcurves

Spectral evolution of RX J0720.4-3125

The Optical Excess

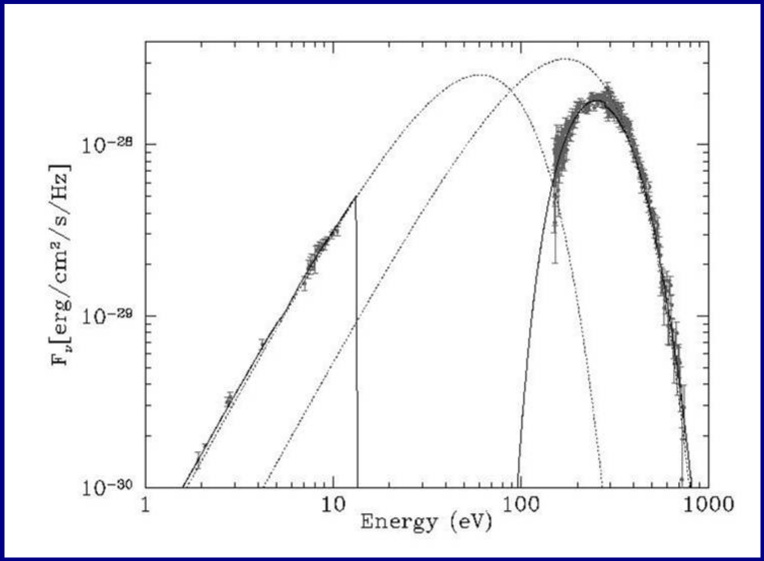


RX J1605 multiwavelength SED (Motch et al 2005)

- In the four sources with a confirmed optical counterpart $F_{opt} \approx$ 5-10 x $B_\nu(T_{BB,X})$
- $F_{opt} \approx \nu^2$?
- Deviations from a Rayleigh-Jeans continuum in RX J0720 (Kaplan et al 2003) and RX J1605 (Motch et al 2005). A non-thermal power law ?

RX J1856.5-3754 - I

Blackbody featureless spectrum in the 0.1-2 keV band (Chandra 500 ks DDT, Drake et al 2002); possible broadband deviations in the XMM 60 ks observation (Burwitz et al 2003)



RX J1856 multiwavelength SED (Braje & Romani 2002)

Thermal emission from NSs is not expected to be a featureless BB ! H, He spectra are featureless but only blackbody-like (harder). Heavy elements spectra are closer to BB but with a variety of features

RX J1856.5-3754 - II

Parallactic distance: D ~ 120-140 pc (Kaplan et al 2002; Walter & Lattimer 2002); D ~ 170 pc (D. Kaplan)

The radiation radius problem

$$R_\infty = 4.25 \left(\frac{D}{100\,\mathrm{pc}} \right) \left(\frac{T_{BB}}{60\,\mathrm{keV}} \right)^{-2} \mathrm{km}$$

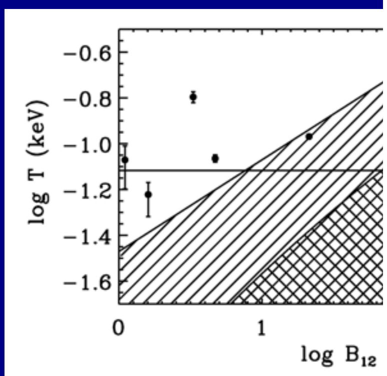
- A quark star (Drake 2002; Xu 2002; 2003)
- … r caps and cooler … n (Pons et al 2002; Braje & Romani 2002; Trűmper et al 2005)

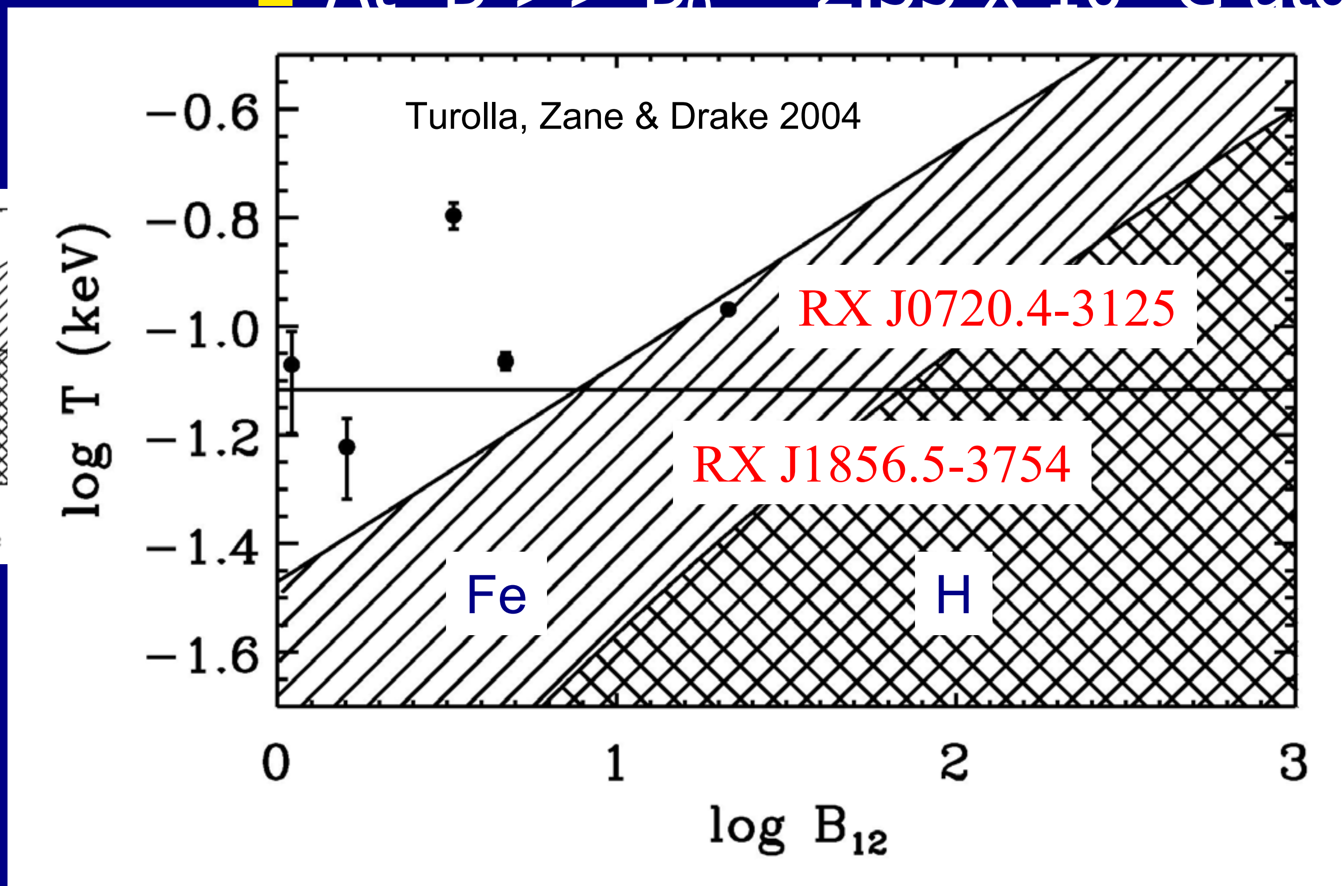
What spectrum ?
The optical excess ?

A perfect BB ?
Pulsations ?

Bare Neutron Stars

- At $B >> B_0 \sim 2.35 \times 10^9$ G atoms





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The Surface Emissivity

The magnetized medium is birefringent: two refracted waves, ordinary and extraordinary

Integrate over the star surface

$$F_\omega = \frac{1}{2}\int_0^\pi f_\omega(\theta)\sin\theta \mathrm{d}\theta$$

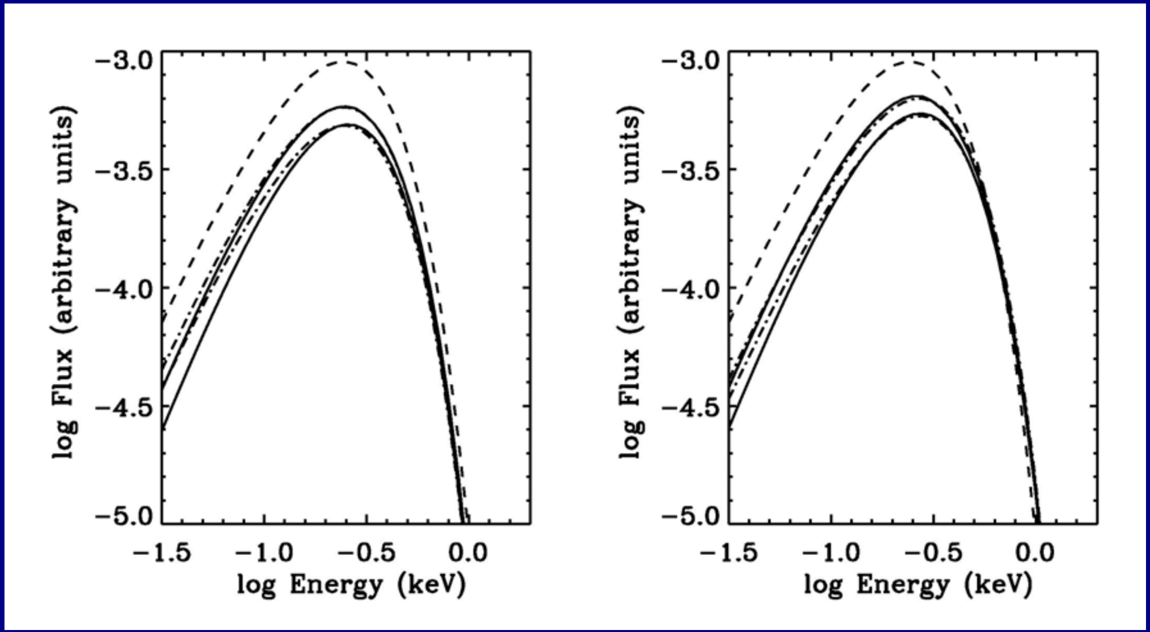
- Compute the reflectivity for a given surface element (Turolla, Zane & Drake 2004)
  - ✓ Solve the dispersion relation for the refractive indices
  - ✓ Use Fresnel equation to derive the amplitude of the reflected wave
  - ✓ ρ_ω is the ratio of the incident to the reflected wave amplitudes and $\alpha_\omega = 1 - \rho_\omega$
- By Kirchhoff law the emissivity is $j_\omega = \alpha_\omega B_\omega(T)$
- The emitted flux is

$$f_\omega = \int_{4\pi} j_\omega(i,\beta,\theta)\sin i \, \mathrm{d}i \, \mathrm{d}\beta$$

Spectra from Bare NSs - I

The cold electron gas approximation. Reduced emissivity expected below ω_p (Lenzen & Trümper 1978; Brinkmann 1980)

Spectra are very close to BB in shape in the 0.1 - 2 keV range, but depressed wrt the BB at T_{eff}. Reduction factor ~ 2 - 3.

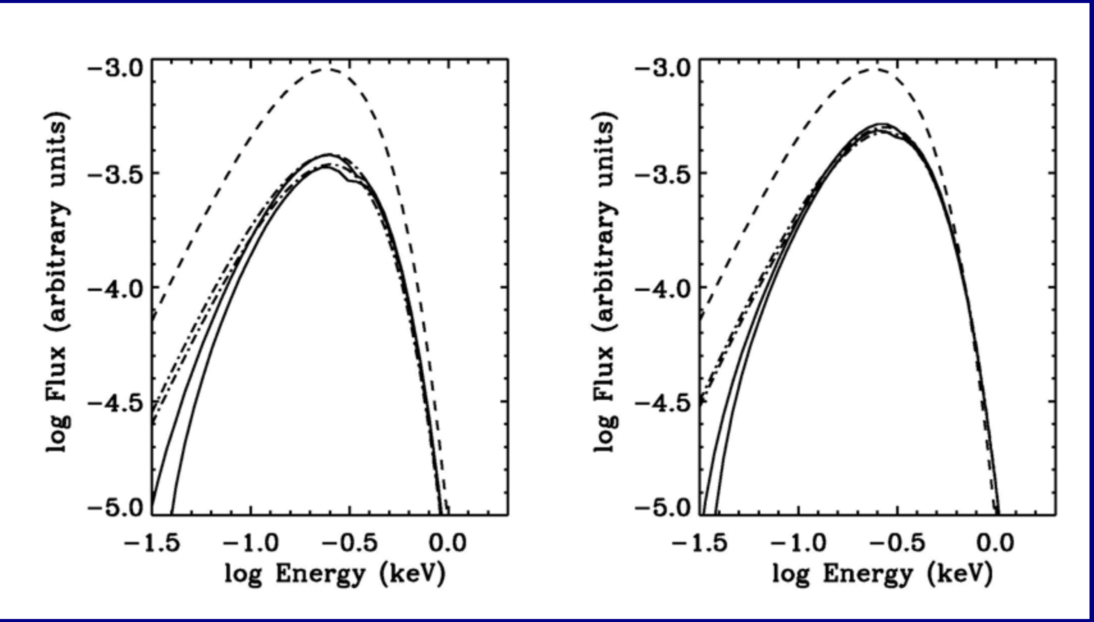


Turolla, Zane & Drake (2004)

Spectra from Bare NS - II

Proper account for damping of free electrons by lattice interactions (e-phonon scattering; Yakovlev & Urpin 1980; Potekhin 1999)

Spectra deviate more from BB. Fit in the 0.1 – 2 keV band still acceptable. Features may be present. Reduction factors higher.

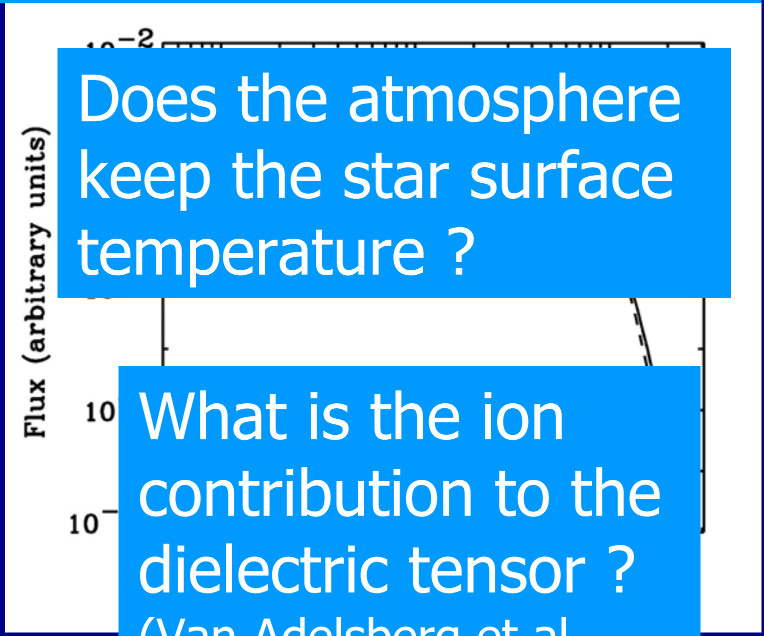


Turolla, Zane & Drake (2004)

Is RX J1856.5-3754 Bare ?

- Fit of X-ray data in the 0.15-2 keV band acceptable
- Radiation radius problem eased
- Optical excess may be produced by reprocessing of surface radiation in a very rarefied atmosphere (Motch, Zavlin & Haberl 2003; Zane, Turolla & Drake 2004; Ho et al. 2006)
- Details of spectral shape (features, low-energy behaviour) still uncertain

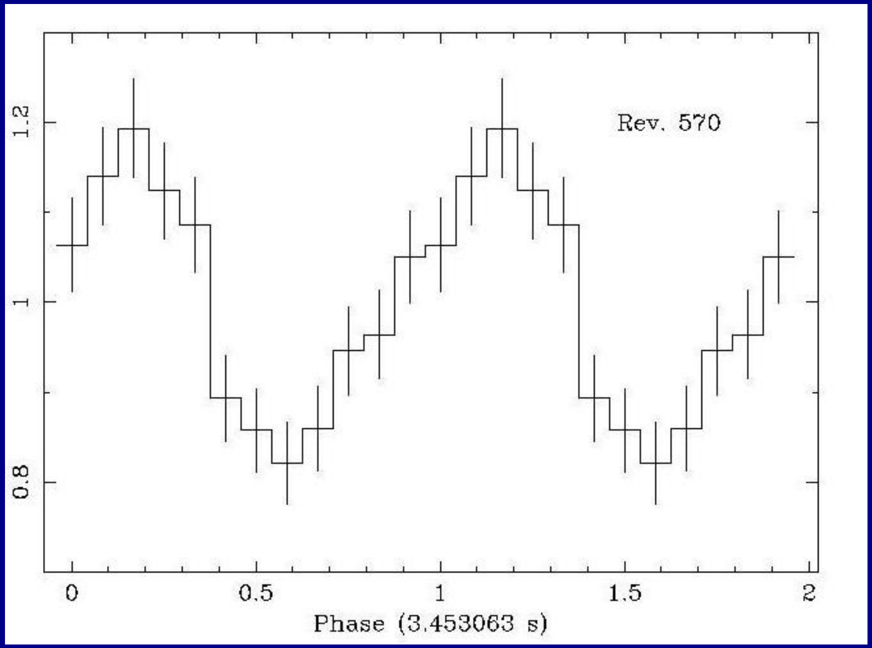
$$R_\infty = 4.25\, f_E^{-1/2} \left(\frac{D}{100\ \mathrm{pc}}\right)\left(\frac{T_{BB}}{60\ \mathrm{keV}}\right)^{-2}\ \mathrm{km}$$



Does the atmosphere keep the star surface temperature ?

What is the ion contribution to the dielectric tensor ? (Van Adelsberg et al. 2005; Perez-Azorin, Miralles & Pons 2005)

Pulsating XDINSs



- Quite large pulsed fractions
- Skewed lightcurves
- Harder spectrum at pulse minimum
- Phase-dependent absorption features at 200-500 eV

Synthetic lightcurves

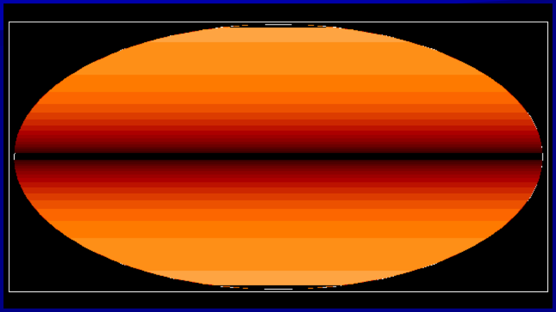
Temperature distribution induced by a dipolar field

Blackbody isotropic emission

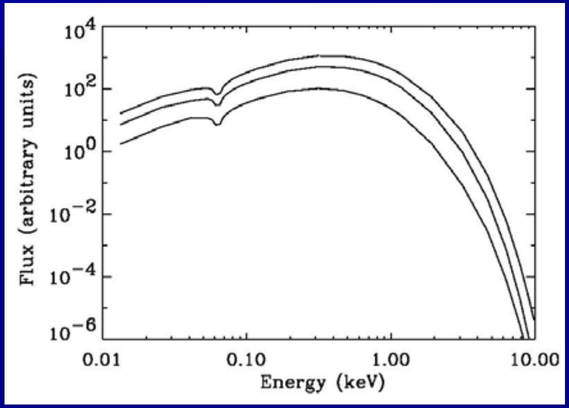
Too small pulsed fractions
Symmetrical pulse profiles
(Page 1995)

- Dipole + radiative (magnetic) beaming ?
- More complicated field geometries (Page & Sarmiento 1996) ?

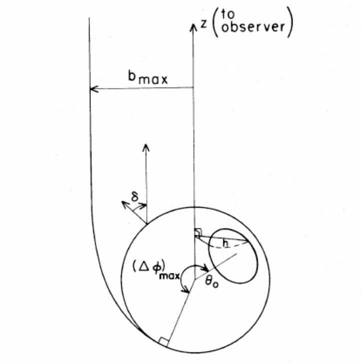
STEP 1
Specify the B-field topology and compute the surface temperature distribution

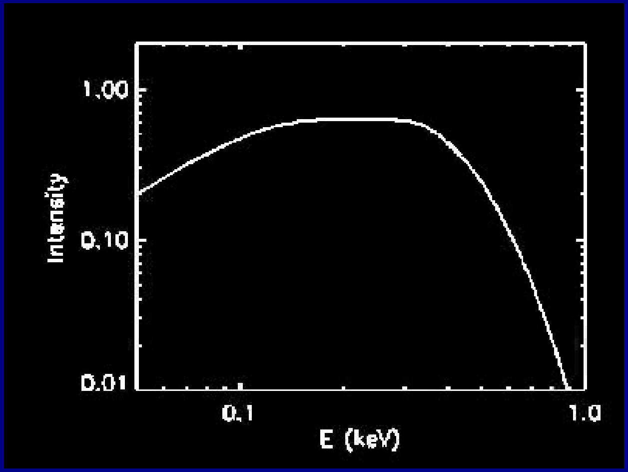


STEP 2
Compute emission at every surface patch



STEP 3
GR ray-tracing to obtain the spectrum at infinity





(just a cartoon !)

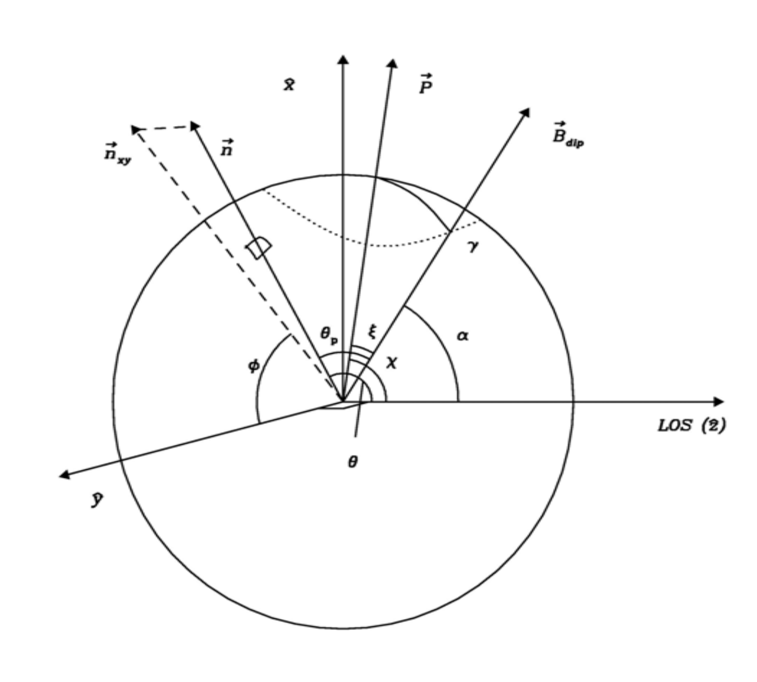
STEP 4
Predict lightcurve and phase-resolved spectrum

Step 1

Fix the magnetic field topology

Compute the surface thermal map:

$$\cos\alpha = \left(\frac{\vec{B}}{B}\right)\cdot\vec{n},\ T = T_p\sqrt{\cos\alpha}$$



Fix the geometry:
χ = angle between LOS and spin axis
ξ = angle between magnetic and spin axis
(Page 1995; Page & Sarmiento 1996; Lloyd et al 2003)

Step 2

First compute all models spanning (so far)

$0.01\,\mathrm{keV} \le E \le 10\,\mathrm{keV}$

$0 \le \cos\alpha \le 1$

$5.4 \le \log T \le 6.6$

$12 \le \log B \le 13.5$

Then interpolate on a common grid and store the 6-D matrix

$$I(E,\mu,\phi,T,B,\alpha)$$

The matrix *I* provides the emerging radiation field at each patch of the neutron star surface

Step 3 and 4

Fix the geometry (angles ξ and χ)
Compute the local polar angles relative to the dipole axis for a given patch (Θ, Φ) and phase γ: $\theta = \theta(\Theta, \Phi, \gamma; \xi, \chi)$, $\varphi = \varphi(\Theta, \Phi, \gamma; \xi, \chi)$

Compute $\boldsymbol{B}(\theta, \varphi)$, $\alpha(\theta, \varphi)$, $T(\theta, \varphi)$

Compute photon angles (GR !)
$\mu = \mu(\Theta, \Phi, \gamma; \xi, \chi)$, $\phi = \phi(\Theta, \Phi, \gamma; \xi, \chi)$

Interpolate $I(E, \mu, \phi, T, B, \alpha)$

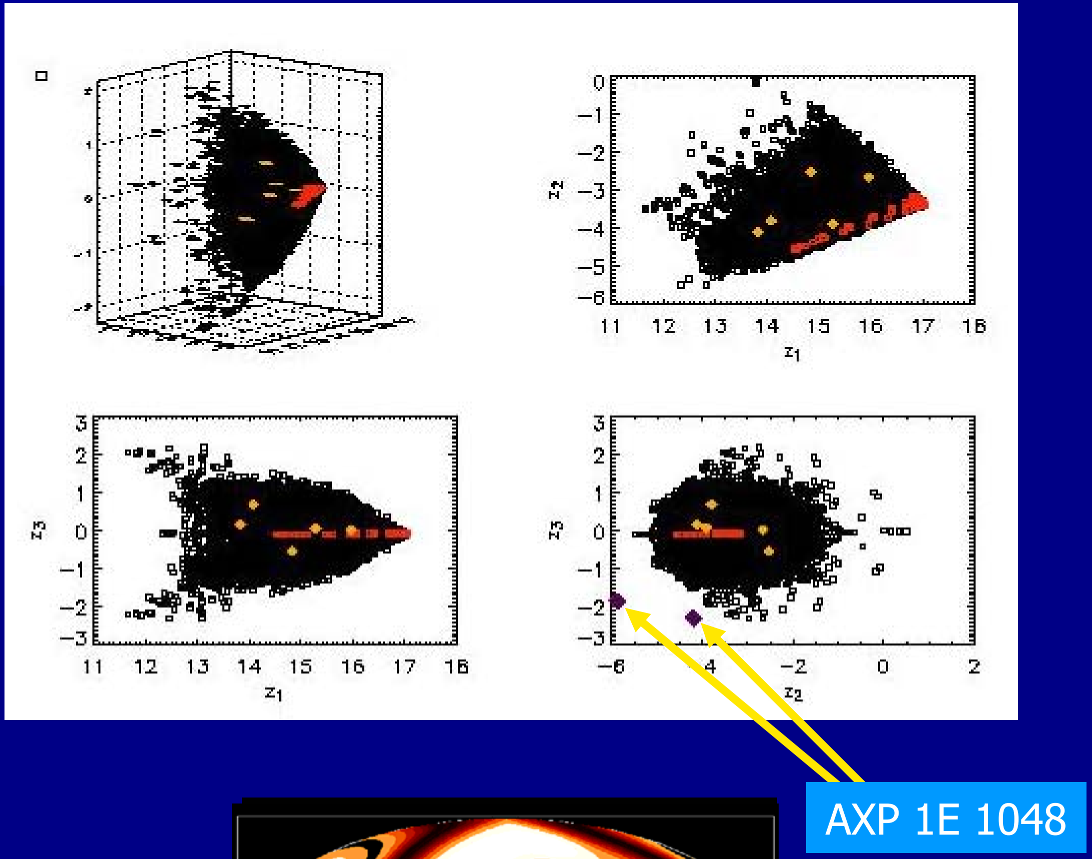
Integrate over the star surface visible at earth

PHASE-DEPENDENT SPECTRUM

LIGHTCURVE

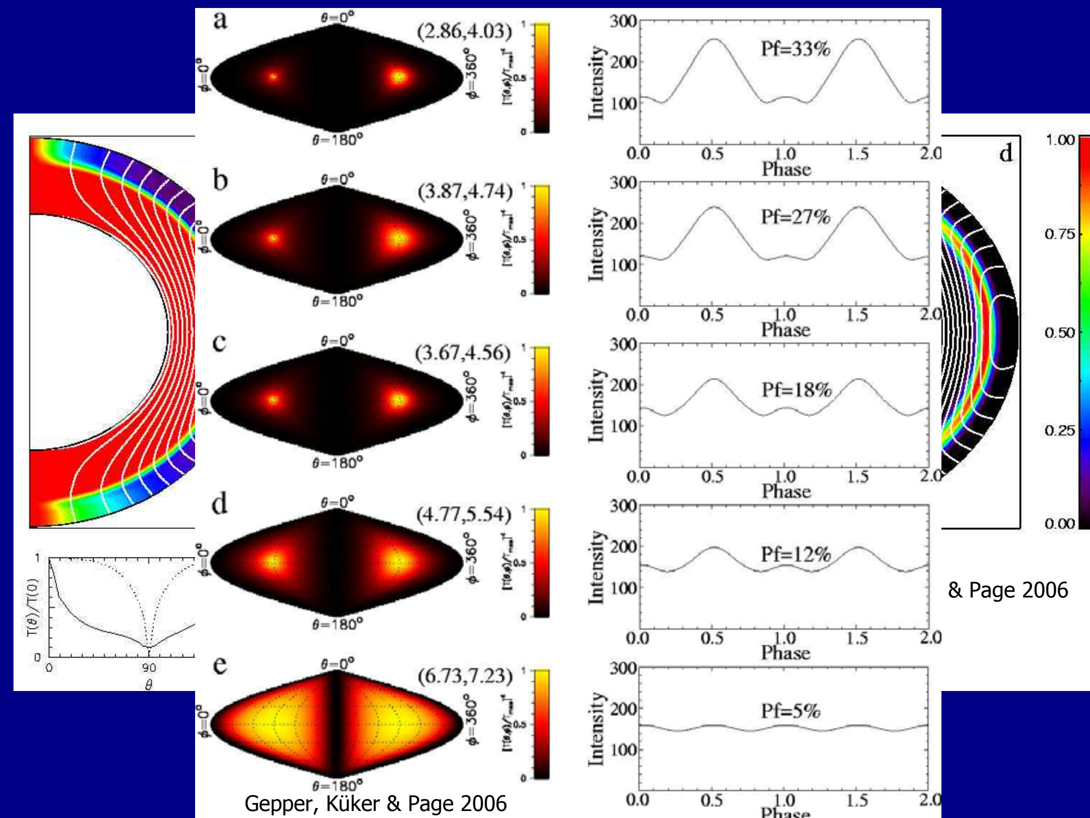
Pure-dipole-induced thermal maps do not match XDINS lightcurves

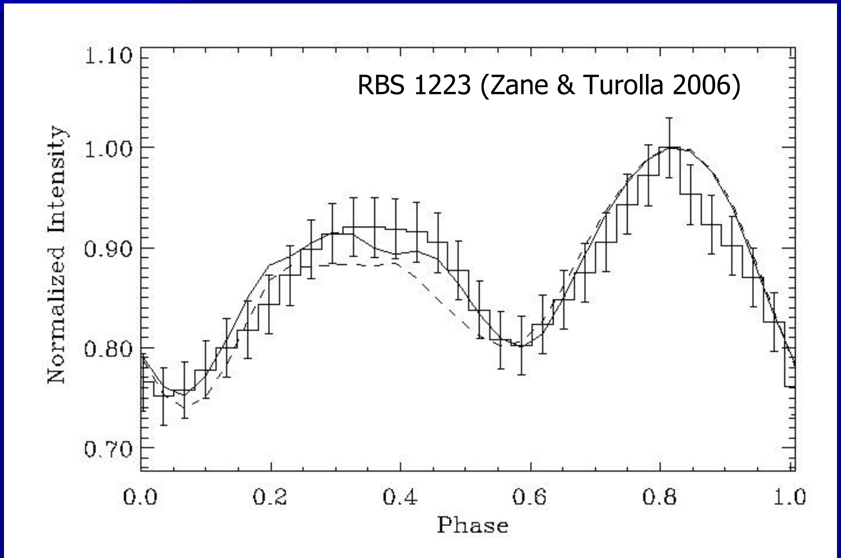
Star-centred dipolar+quadrupolar fields can reproduce observed lightcurves (Zane & Turolla 2006)

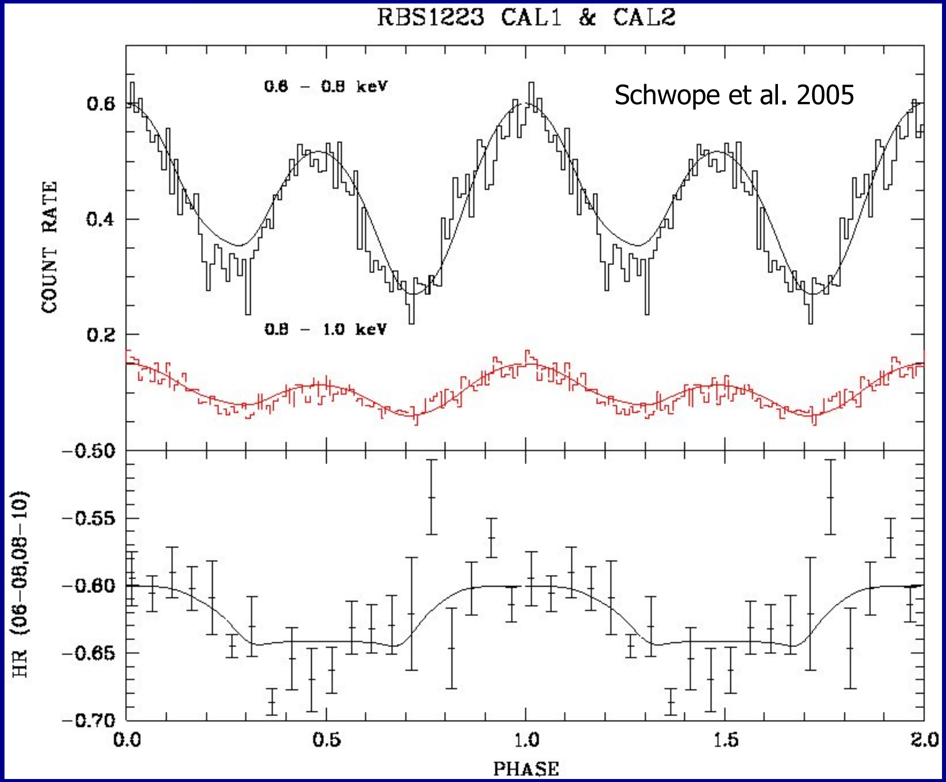


Crustal Magnetic Fields

- Star centered dipole + poloidal/toroidal field in the envelope (Geppert, Küker & Page 2005; 2006)
- Purely poloidal crustal fields produce a steeper meridional temperature gradient
- Addition of a toroidal component introduces a N-S asymmetry

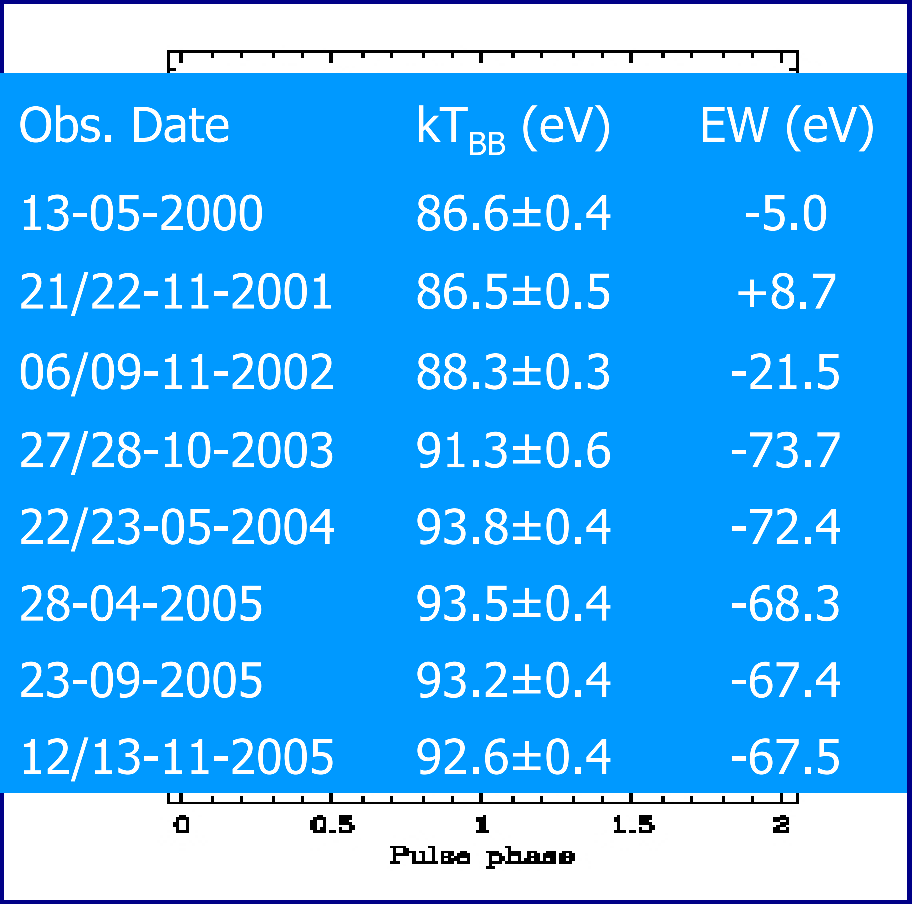



RBS 1223 (Zane & Turolla 2006)
Normalized Intensity
1.10
1.00
0.90
0.80
0.70
0.0
0.2
0.4
0.6
0.8
1.0
Phase


RBS1223 CAL1 & CAL2
Schwope et al. 2005
0.6 – 0.8 keV
0.8 – 1.0 keV
COUNT RATE
0.6
0.4
0.2
HR (06–08,08–10)
−0.50
−0.55
−0.60
−0.65
−0.70
0.0
0.5
1.0
1.5
2.0
PHASE

Long Term Variations in RX J0720.4-3125

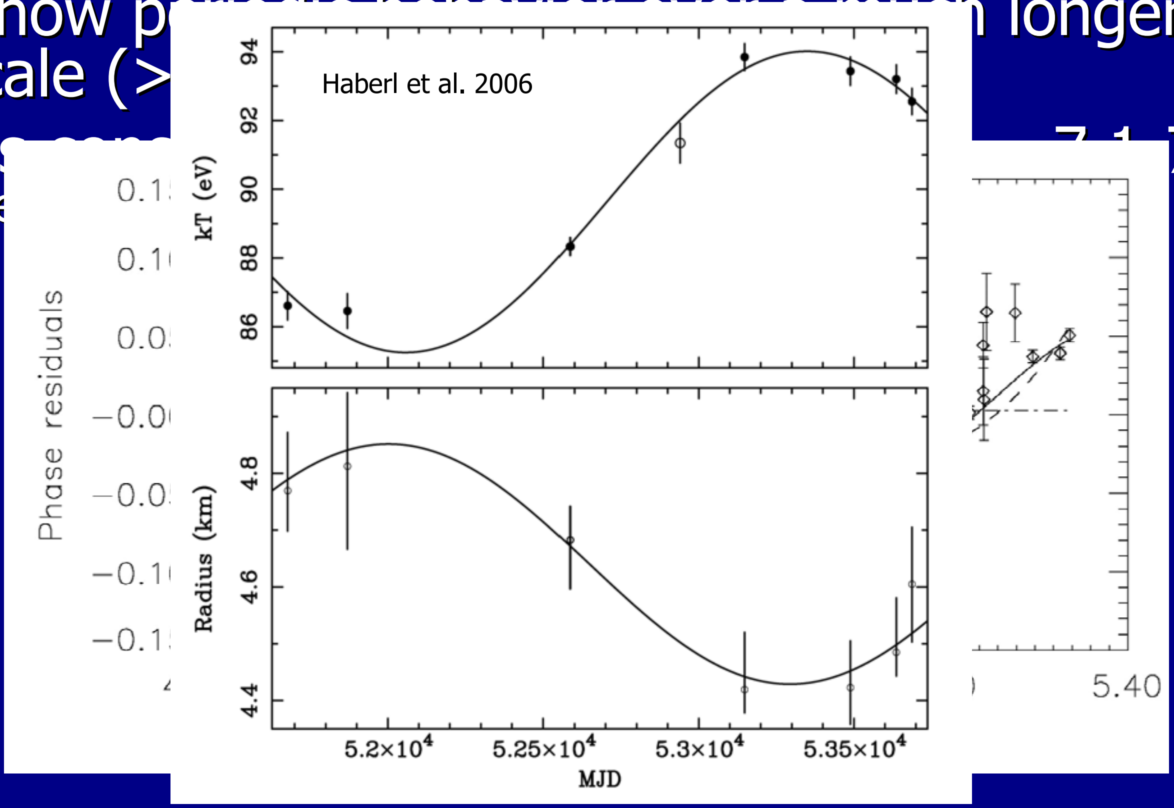
- A gradual, long term change in the shape of the X-ray spectrum AND the pulse profile (De Vries et al 2004; Vink et al 2004).
- Steady increase of T_{BB} and of the absorption feature EW (faster during 2003)
- Evidence for a reversal of the evolution in 2005 (Vink et al. 2005)



Obs. Date	kT_{BB} (eV)	EW (eV)
13-05-2000	86.6±0.4	-5.0
21/22-11-2001	86.5±0.5	+8.7
06/09-11-2002	88.3±0.3	-21.5
27/28-10-2003	91.3±0.6	-73.7
22/23-05-2004	93.8±0.4	-72.4
28-04-2005	93.5±0.4	-68.3
23-09-2005	93.2±0.4	-67.4
12/13-11-2005	92.6±0.4	-67.5

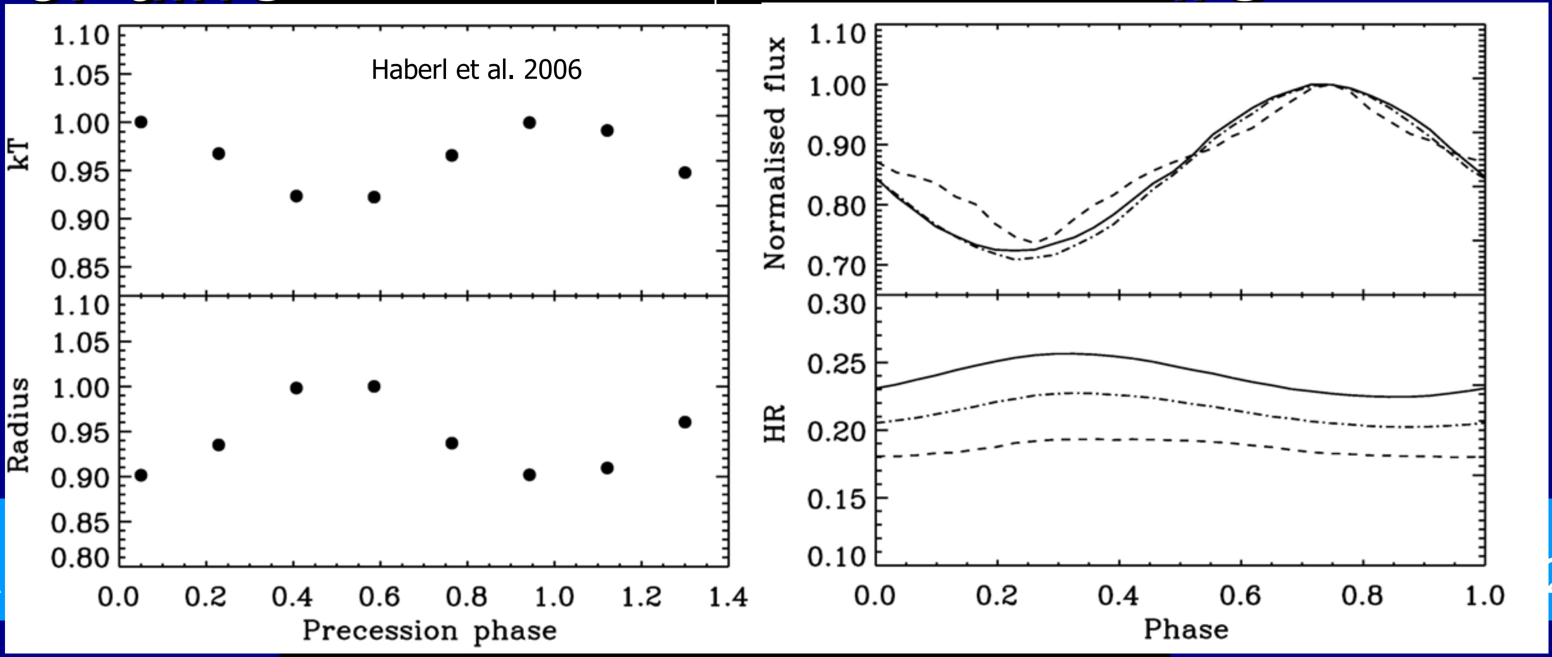
A Precessing Neutron Star ?

- Evidence for a periodic modulation in the spectral parameters (T_{bb}, R_{bb}) but no complete cycle yet
- Phase residuals (coherent timing solution by Kaplan & Van Kerkwijk 2005) show p… longer timescale (>…
- Periods … 7.1-7.7 yr (Haberl e…



A Simple Model

- Precessing neutron star
- Blackb[redacted]hot spots" of diffe[redacted]ure



A … 2006)

Conclusions

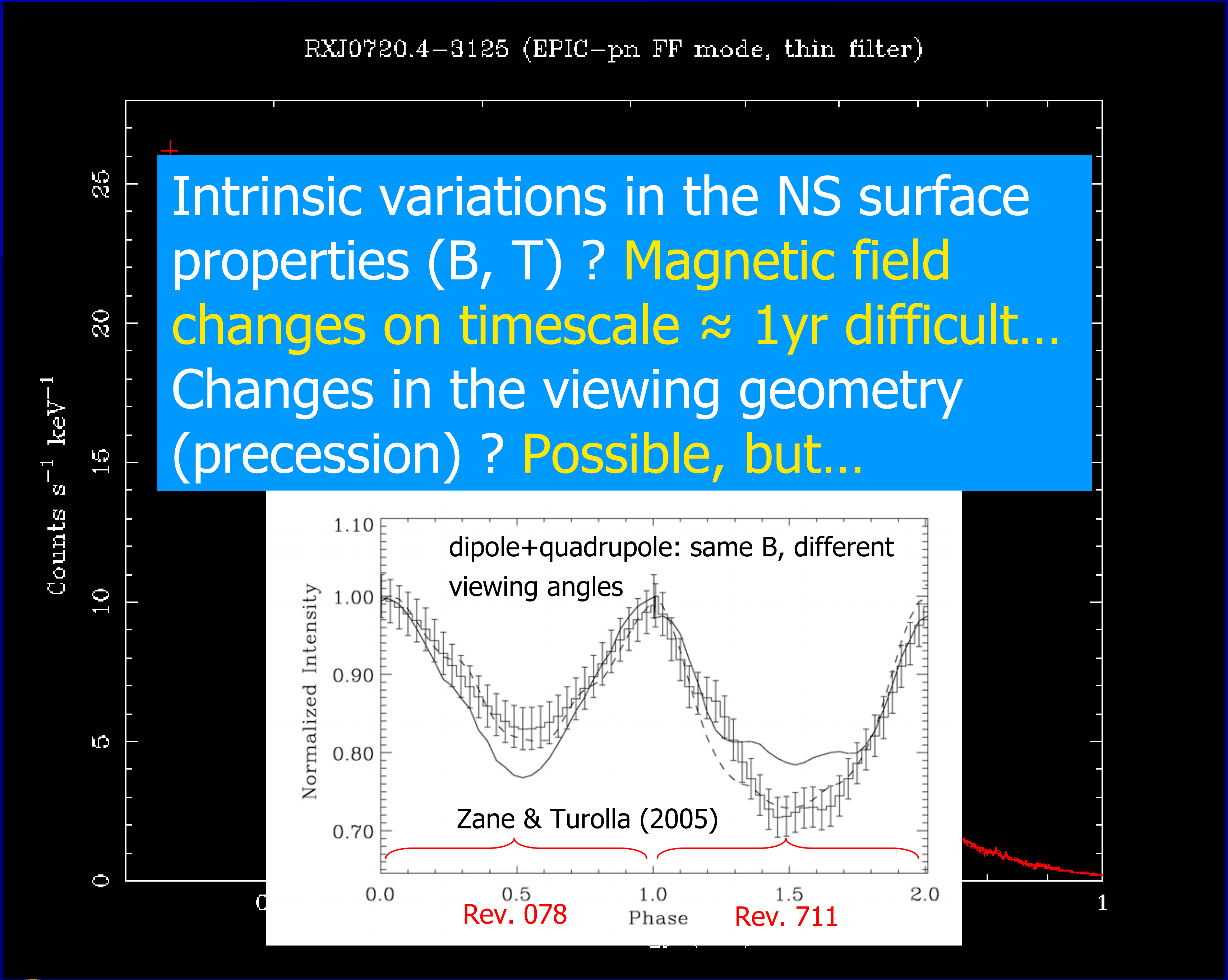
- Rather complex thermal maps required to explain XDINS observations
- Progresses on the theoretical side but no self-consistent model yet
  - crustal fields (outside axial symmetry)
  - phase transition and emission properties of condensed surface
  - radiative transfer in the $B > B_{QED}$ regime
- Find more sources (searches in progress: Agueros et al 2006, Chieregato et al 2005)
  - is RX J1856.5-3754 unique ?
  - Relationship with other NS populations:
    - Pulsating XDINSs are quite likely strongly magnetized objects, $B > 10^{13}$ G. A XDINS-magnetar connection ?
    - XDINSs = RRATs ? (McLaughlin et al 2006; Popov et al 2006)
    - the Galactic NS census

Source	Energy (eV)	EW (eV)	B (10^{13} G)	Notes
RX J1856.5-3754	no	no	?	Non pulsating
RX J0720.4-3125	270	40	5	Variable line
RX J0806.4-4123	460	33	9	-
RX J0420.0-5022	330	43	7	-
RX J1308.6+2127	300	150	6	-
RX J1605.3+3249	450	36	9	-
1RXS J214303.7+065419	700	50	14	-

Period Evolution

- RX J0720.4-3125: bounds on $\dot{P}$ derived by Zane et al. (2002) and Kaplan et al. (2002)
- Timing solution by Cropper et al. (2004), further improved by Kaplan & Van Kerkwijk (2005): $\dot{P} = 7\text{x}10^{-14}$ s/s
- RX J1308.6+2127: timing solution by Kaplan & Van Kerkwijk (2005a), $\dot{P} = 10^{-13}$ s/s
- Spin-down values of B in agreement with absorption fe… …yclotron lines !

$B \sim 10^{13}$ -10^{14} G !



Intrinsic variations in the NS surface properties (B, T) ? Magnetic field changes on timescale ≈ 1yr difficult…

Changes in the viewing geometry (precession) ? Possible, but…