Neutron Star Surface Emission: beyond the dipole model

Silvia Zane, MSSL, UCL

Dim Isolated neutron stars are key in compact objects astrophysics: these are the only sources in which we can see directly the "surface" of the compact star.

If pulsations and/or long term variations are detected:

1) Study shape/evolution of the pulse profile of the thermal emission

2) Information about the thermal/magnetic map of the star surface.

X-ray Pulsating Dim Isolated Neutron Star: 5 so far!

Object	kT/eV	E_{line}/eV	P (s)	semiampl	opt.
RX J0420.0-5022	44	329	3.45	12%	B>25.5
RX J0720.4-3125	85	270	8.39	11%	B=26.6
RX J0806.4-4123	96	460	11.37	6%	B>24
RBS 1223	86	290	10.31	18%	m=28.6
RBS 1556	96	493			m=26.8
RX J1856.5-3754	60			<1%	V=25.7
RBS 1774	100	700	9.5	4%	R>23

- Soft X-ray sources in ROSAT survey; no radio emission
- BB-like X-ray spectra, no non thermal hard emission
- Low absorption, nearby ($N_H \sim 10^{19}$-10^{20} cm^{-2})
- Constant X-ray flux over ~years: BUT 0720!
- No obvious association with SNR
- Optically faint
- THEIR SPECTRUM CANNOT BE REPRODUCED BY SINGLE T/SINGLE B ATMOSPHERIC MODELS!

Evidence for a complex surface thermal and magnetic map:

1) LC's may be asymmetric (skewness)

2) Relatively large pulsed fractions: 12%-35%

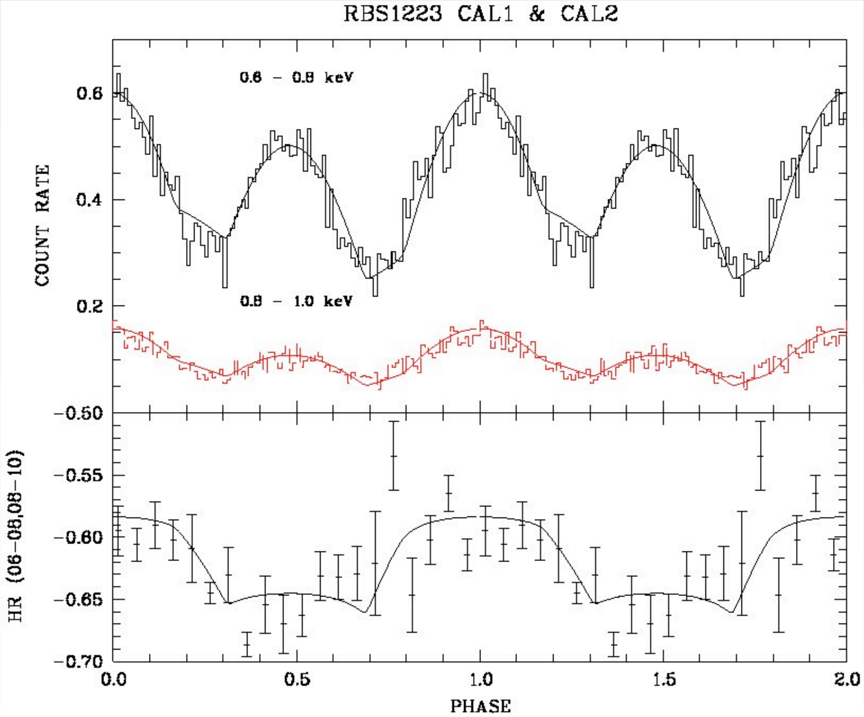
3) Absorption features change with spin phase

4) All cases: hardness ratio is max at the pulse maximum: counter-intuitive!

⇒ Beaming effects ? (Cropper et al. 2001)
⇒ Phase-dependent cyclotron absorption? (Haberl et al., 2003)

Further evidence for a complex surface thermal and magnetic map: 1) the case of RBS 1223

The lc is double peaked
Max separation 0.47 phase units
Min separation 0.43 phase units



Schwope et al 2005:
Two caps model
BB emission, GR light bending
(no radiative beaming)

T_1 = 92 eV T_2=84 eV

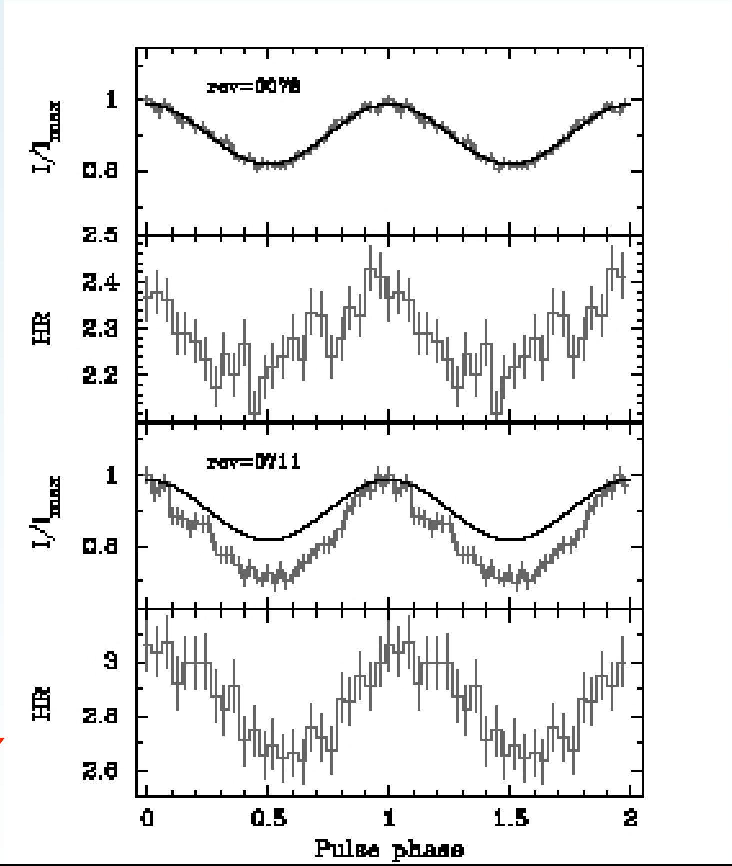
Minimum Spot separation =130°
ξ= B•Ω = 80°
χ= LOS •Ω =80°

… 2) the case of RXJ0720: long term variations

De Vries et al., 2004
Vink, et al, 2004

A gradual, long term change in the shape of the X-ray spectrum AND in the pulse profile

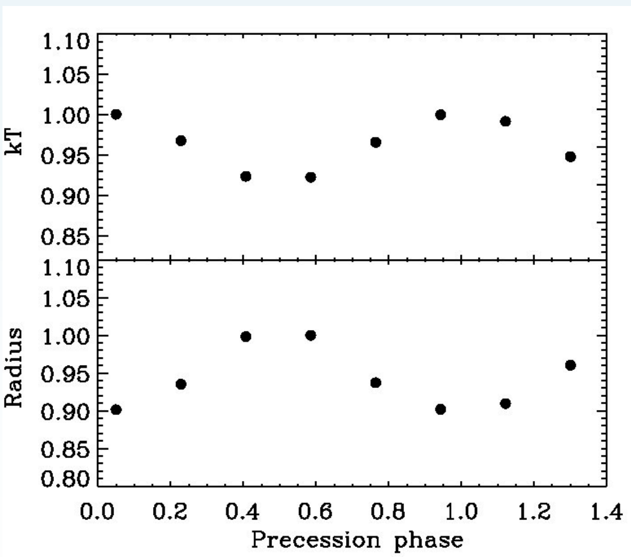
From rev. 78 (13 May 2000) to rev.711 (27-10-2003) the pulse profile become narrower and the pulsed fraction increases from ~20% to ~ 35%

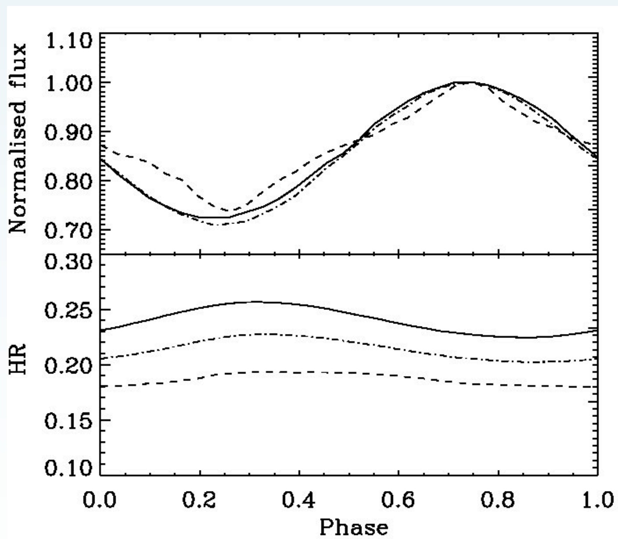


Pulse profile of 0720 in the 0.1-1.2 keV band and hardness ratio. The best sinusoidal fit to rev. 0078 (solid line) is overplotted on the light curve of rev. 0711 for comparison.

… 2) the case of RX J0720

Long term variations can be explained by precession over a period of ~7 yrs (see talk by Frank Haberl and a poster by Jacco Vink)





Haberl et al 2006:

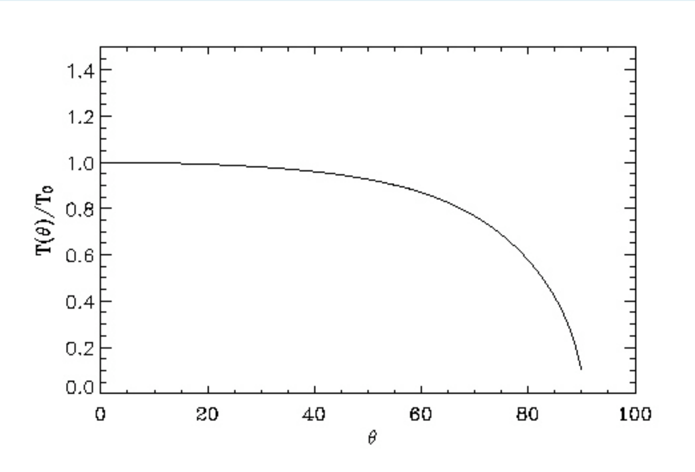
Two spot model
BB emission
GR light bending
(no radiative beaming)
T_1 =80 eV
T_2= 100 eV

Spot separation = 160°
ξ= B•Ω = 75°
χ= LOS •Ω =5°

Evidence for two hot spots, non exactly antipodal; high pulsed fraction, skewness, time variations… What may cause such a complex surface thermal map?

A dipolar B-field only gives a Greenstein & Hartke map (1983) ⇒ always symmetrical and quite smooth

$$T(\vartheta) \propto \frac{K + (4-K)\cos^2\vartheta}{1+3\cos^2\vartheta}$$



⇒ To have a non symmetric lightcurve shape we need:

i) quadrupolar components,
ii) radiative beaming (no isotropic emission)
iii) or both..

Model / Feature	Blackbody +dipole	Atmosphere +dipole	Blackbody +quadrupole
Pulsed fraction	No, too low Page (1995)	Yes Shibanov et al (1995)	Yes Page & Sarmiento (1996)
Lightcurve shape	No, always symmetrical Page (1995)	No, always symmetrical	Yes Page & Sarmiento (1996)
Line changes with phase	Does not apply	?	Does not apply
Long-term variations	?	?	?

Relatively large pulsed fraction (up to 20%) are achieved accounting for:

- Radiative beaming (atmo models and field assumed dipolar; Shibanov et al, 1995)

- Quadrupolar B- components (emission assumed bb-like and isotropic; Page, D. 1995, Page and Sarmiento, 1996)

- both effects, self-consistently (Zane and Turolla, 2006)

As far as two caps non antipodal, there are two natural ways to reach this non axisymmetry:

- By complicating the external topology (as in Zane and Turolla 2006)

- By assuming that the external field is still a dipole, but the crustal field is not (e.g. Geppert, Kuker and Page 2004, 2005).

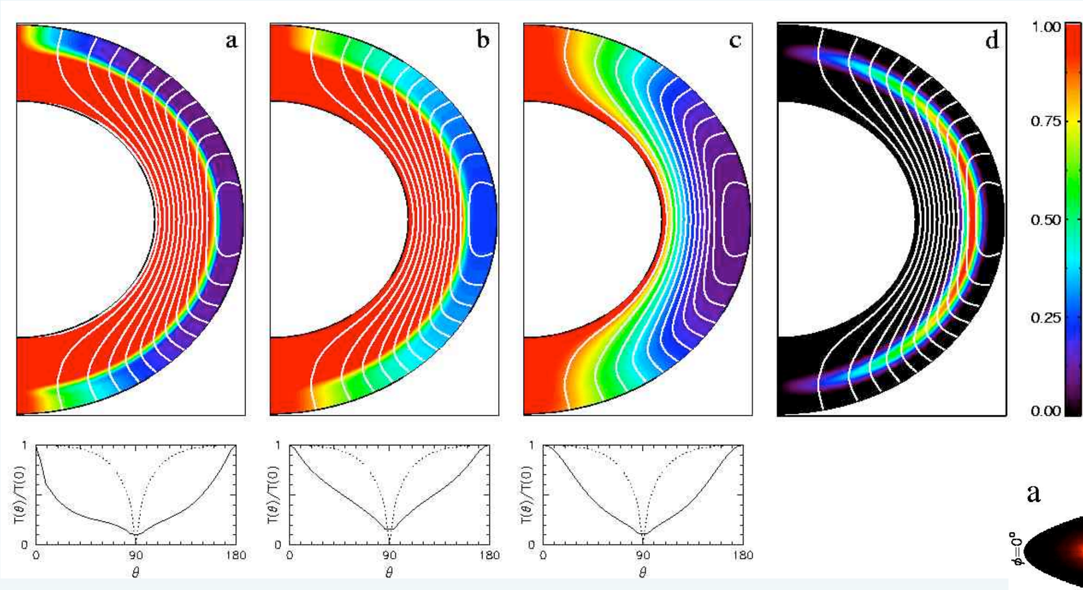
- If the $B_{meridional}$ dominates over B_{radial} in a large part of the crust (e.g. if the B-field is entirely confined in the crust), the non-uniformity of T is not restricted to the envelope, but may extend to the whole crust ⇒ surface T map different from Greenstein & Hartke model

- If the field is localized in the core ⇒ the crustal field is dipolar, the crust is isothermal and the non-uniformity of the surface T map is only due to field effects in the envelope.

Geppert, Kuker & Page, 2004/2005: more realistic field geometries with currents associated to the dipolar field distributed in crust and core + strong toroidal components. The external field is still assumed to be a dipole!

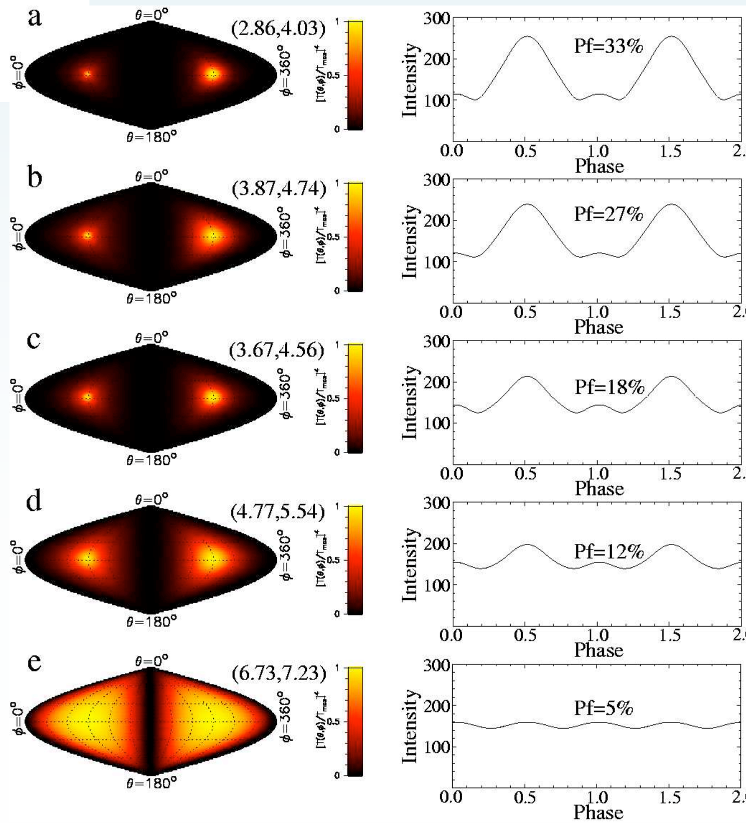
Theoretical support:

1) a stable magnetic field configuration needs a coexistence of poloidal and toroidal magnetic fields with ~the same strength (few pap by Markay & Tayler, 1973)
2) A proto ns dynamo is unlikely to generate purely poloidal fields ⇒ differential rotation will easily wrap a dipole and generate strong toroidal components (Kluzniak & Ruderman 1998, Wheeler et al, 2002). Effect enhanced by magneto-rotational instability (Balbus & Hawley, '91)



a,b,c:Thermal structure of the crust for $B^{tor} = 10^{15}$ G and $B^{pol} = 10^{12}, 10^{13}, 10^{14}$ G.
d: structure of the magnetic field: Field lines are for the poloidal component, while colors show the isolines of a toroidal component with unit polar strength

Surface Flux (T4) distributions:
a,b: Bcrust > Bcore
c,d: Bcore > Bcrust
e: isothermal crust



From Geppert, Kuker & Page, 2005

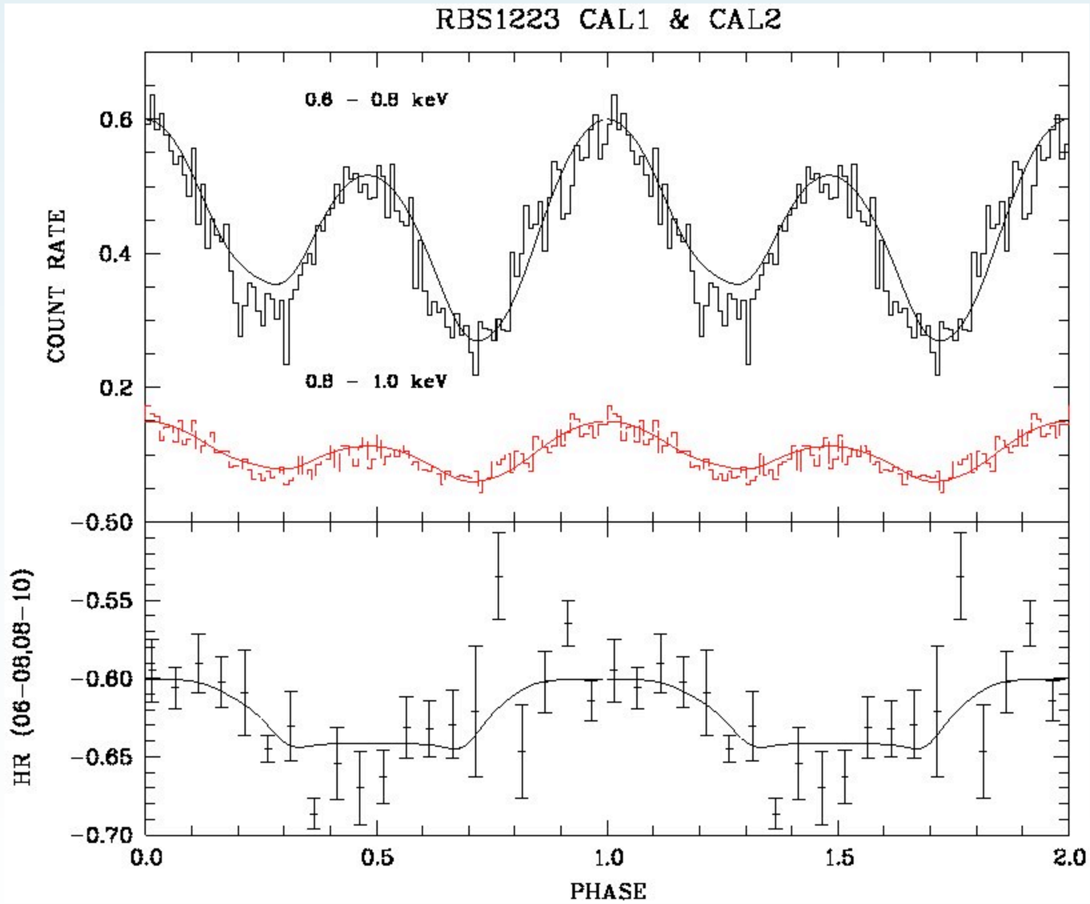
An attempt to reproduce the lc of RBS 1223 with toroidal + poloidal fields (Schwope et al, 2005)

BUT:

1) Data require two different spots ⇒ star artificially divided in two hemispheres and two models with different field parameters are used.

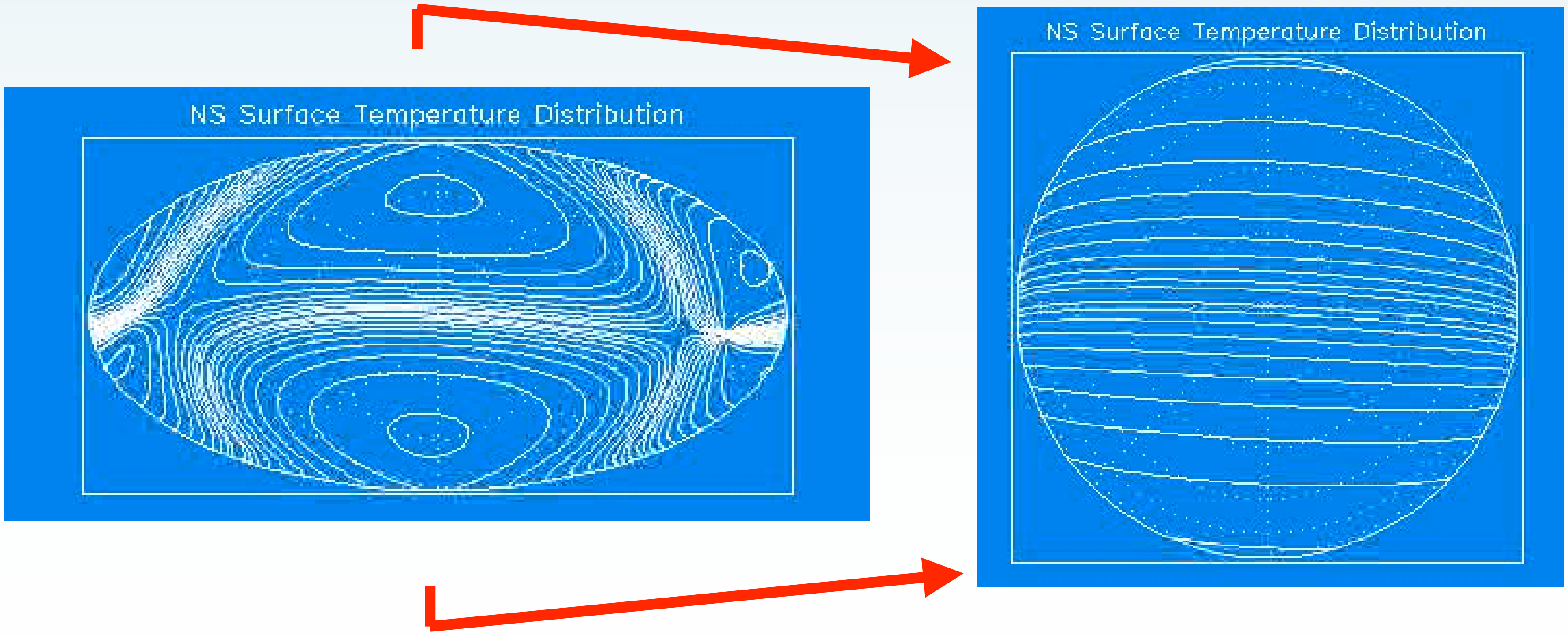
2) Evidence for non antipodal spots ⇒ Hemispheres are than inclined wrt to each other.

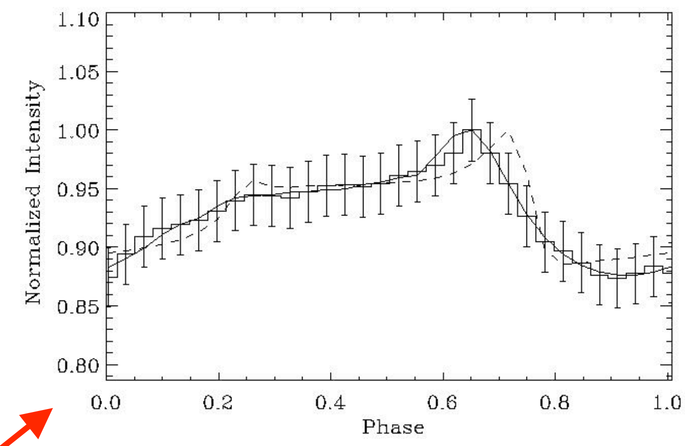
3) No radiative bending



Alternative: a complex topology in the external field (Zane & Turolla 2006)

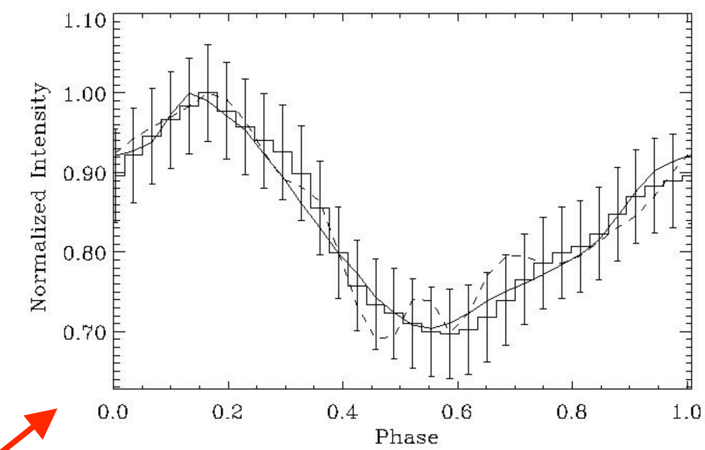
1) Fix a given dipolar + quadrupolar configuration and compute consistently the thermal map of the surface
2) Build an archive of atmospheric models at different T, B, α (magnetic inclination angle) and store the specific intensity I (E, θ, φ, T, B, α)
3) By using the matrix I we can associate at every patch of the neutron star surface the frequency dependent emissivity.
4) GR bending included





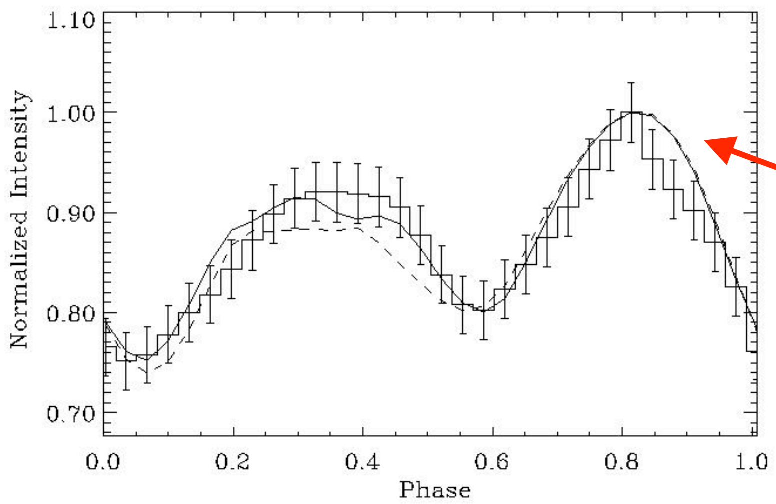
RXJ 0806, rev 618 (0.12-1.2 keV; EPIC-PN, data from Haberl et al, 2004)

B^0quad = 0.39 Bdip; B^1quad = -0.37 Bdip;
B^2quad = 0.12 Bdip; B^3quad = -0.13 Bdip;
B^4quad = 0.49 Bdip; χ = 59.2 ξ = 0.0



RXJ 0420, rev 570 (0.12-0.7 keV, EPIC-PN, data from Haberl et al, 2004)

B^0quad = -0.48 Bdip; B^1quad = 0.02 Bdip;
B^2quad = -0.25 Bdip; B^3quad = 0.35 Bdip;
B^4quad = -0.20 Bdip; χ = 91.2 ξ = 39.9



RXJ 1223, rev. 561 (0.12-0.5 keV, EPIC-PN, data from Haberl et al, 2003)

B^0quad = 0.21 Bdip; B^1quad = -0.02 Bdip
B^2quad = 0.12 Bdip; B^3quad = -0,13 Bdip
B^4quad = 0.50 Bdip; χ = 95.1 ξ = 0.0

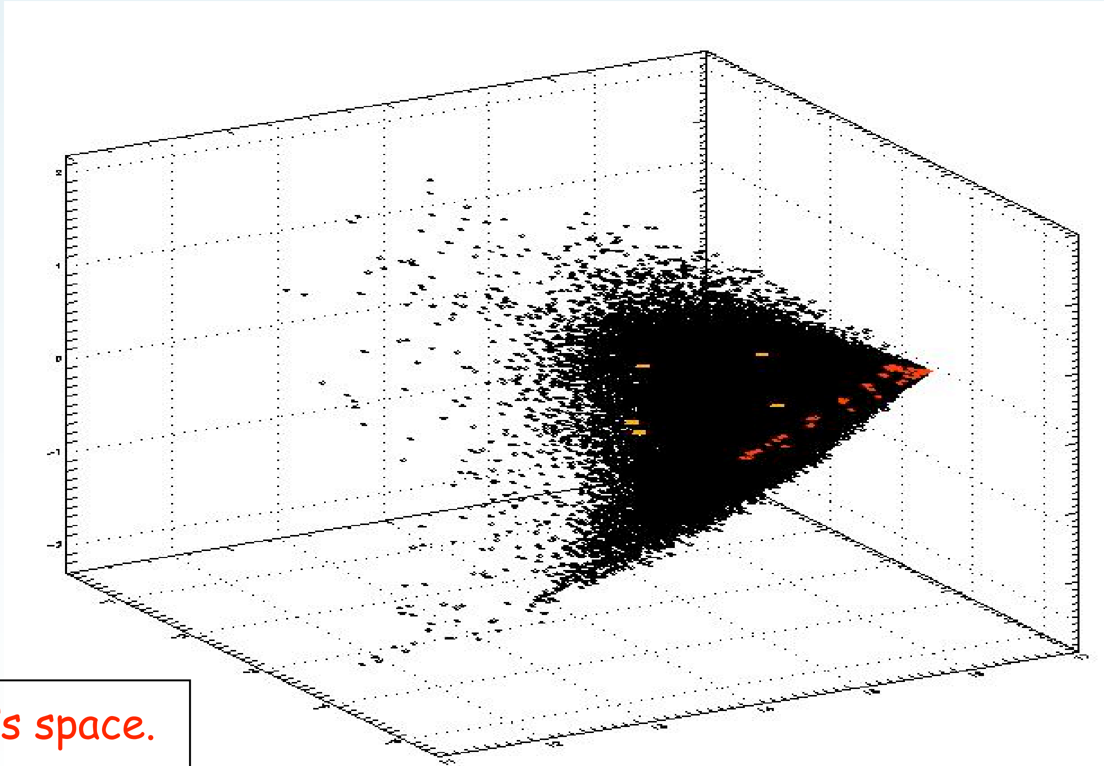
From Zane & Turolla 2006

Principal Component analysis.

We built a grid of 78000 models varying B^i_{quad} (i=0,…4), χ, ξ + 100 dipolar models varying χ, ξ

LCs close to each other in the PCs space have similar characteristics

The first 3 z's account for 72% of the total variance!



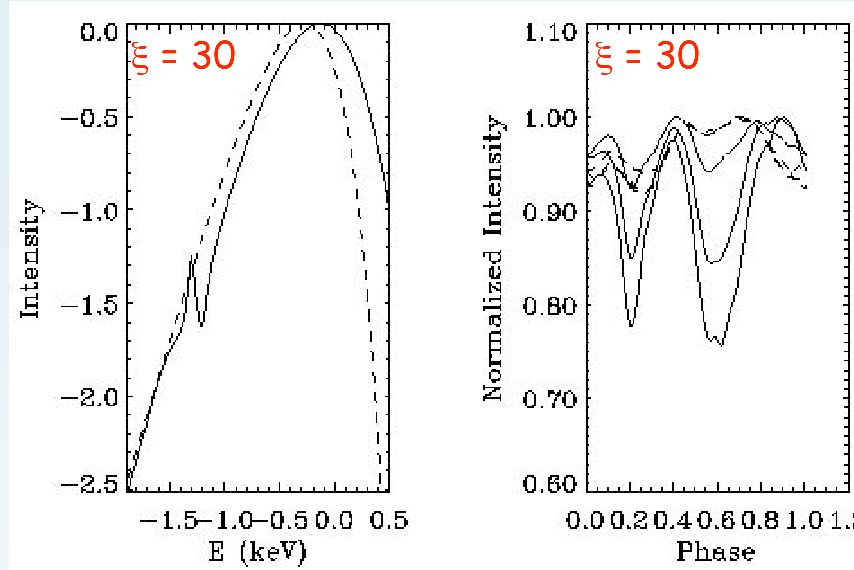
LCs distribution in the first 3 PCs space.
- Red dots : dipolar models
- Black dots :quadrupolar models
- Yellow dots: XDINSs lcs

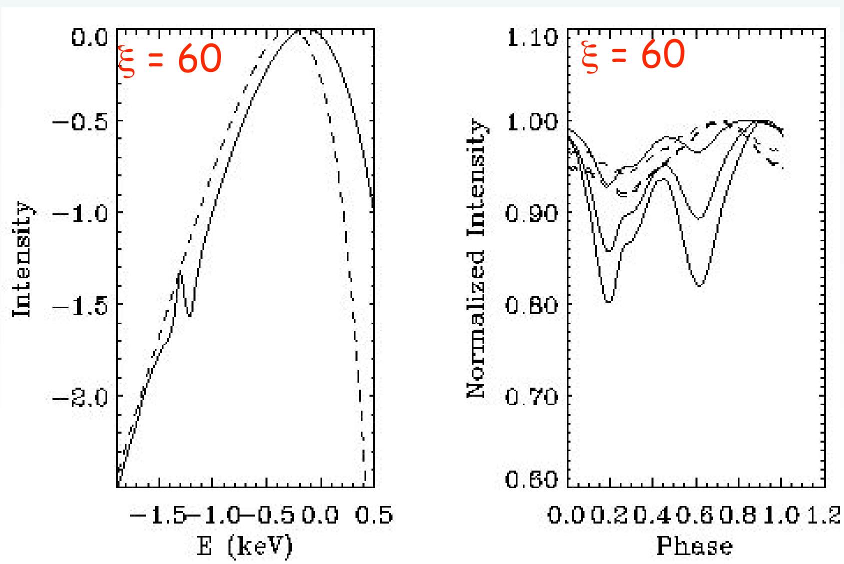
From Zane & Turolla 2006

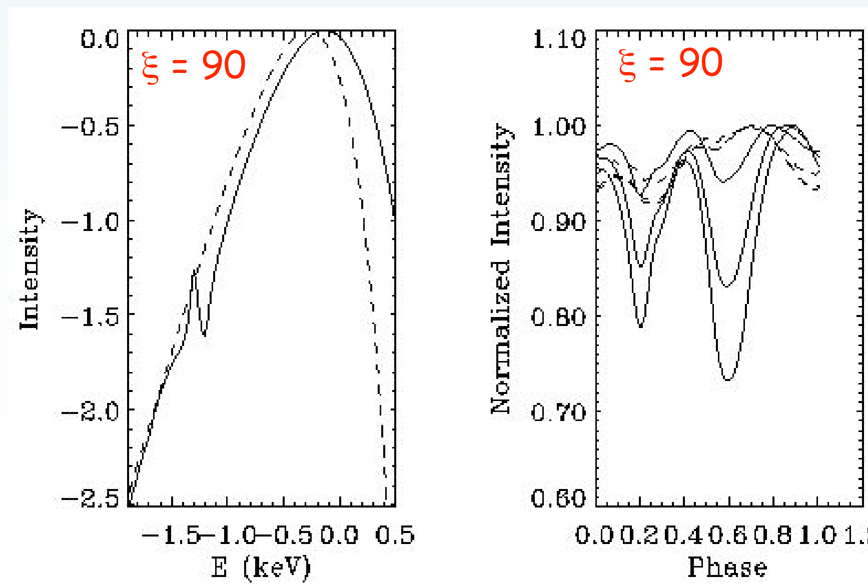
Effects of radiative beaming:

B_{dip} = 6 x 10^{12} G, T_{pol} = 2.5 MK
B^0_{quad} =0.5 B_{dip}, B^2_{quad} =0.9 B_{dip}
χ = 90

---- bb emission (spectrum and lc in 3 bands)
——— atmo emission (spectrum and lc in 3 bands)



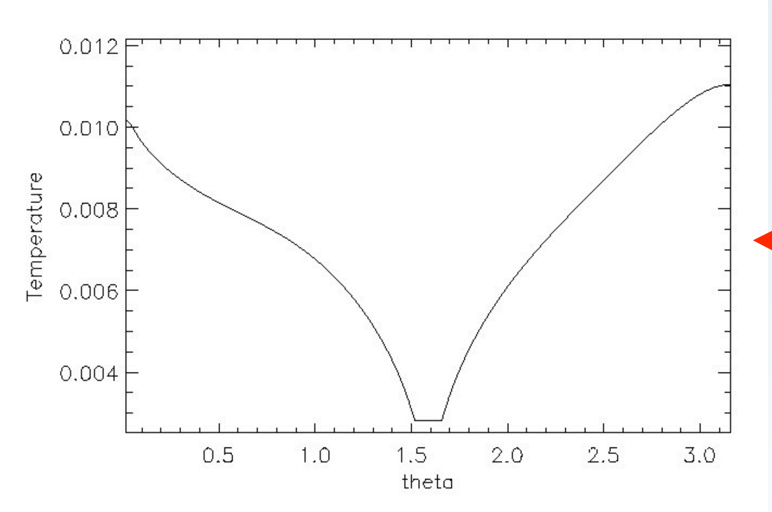




From Zane & Turolla 2006

Effects of radiative beaming and toroidal components in the crustal field

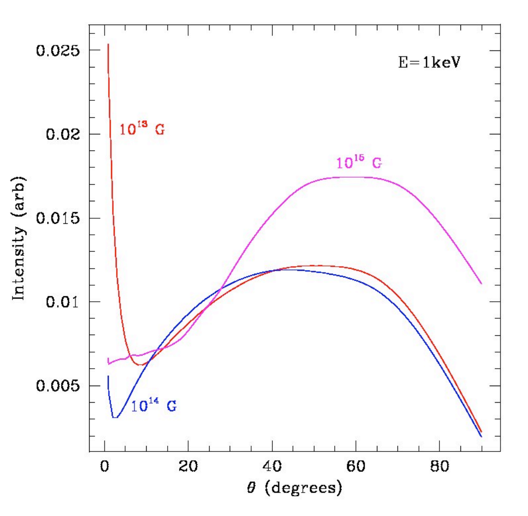
(Zane, Turolla, Geppert and Albano in prep)



B=6e12 G
T surface ~ 1.2 e6 K

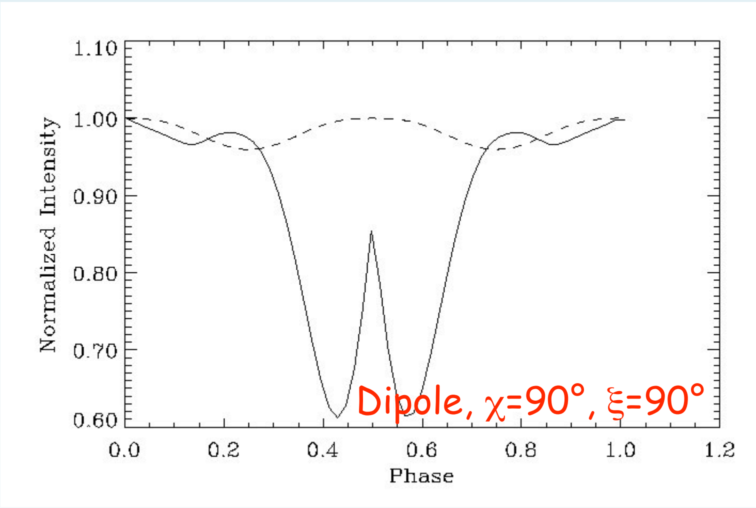
B^0_{crust} = 3e12 G
B^0_{core}= 3e12 G
B^0_{tor} = 1e15 G

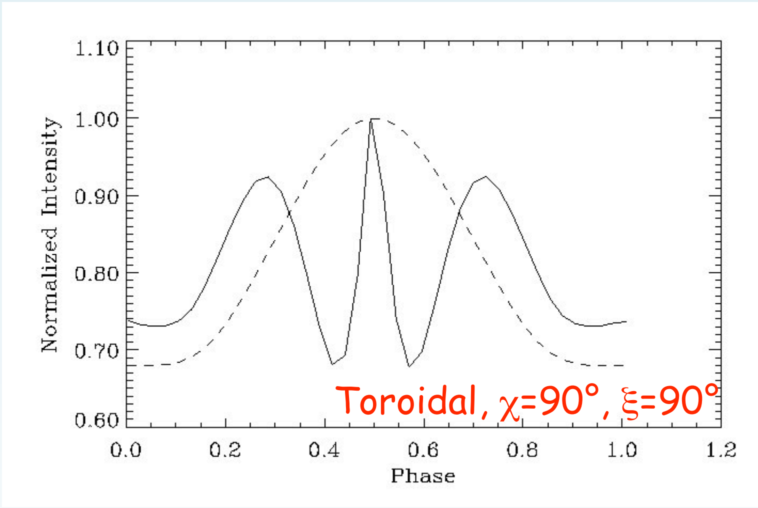
Max of toroidal field at x_{core}+ 0.2 (x_{crust} -x_{core})
(Model as in Geppert at al, 2005)

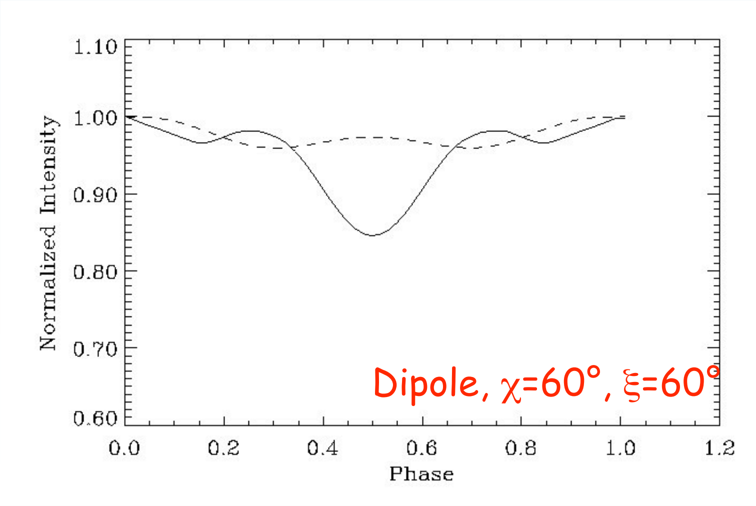


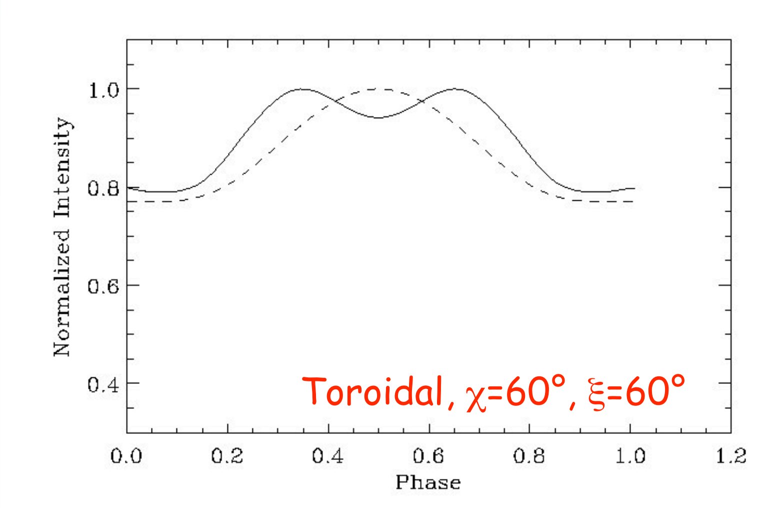
Magnetic cross section is highly angle-dependent:
Narrow pencil beam at small angles (<5°)
Broad pencil beam at 20°-60°
⇒ INTERPULSES !
(Ozel, 2001/2002)

Interpulses are particularly visible for orthogonal rotators, and even more if one of the caps is colder than the other due to toroidal fields effects!







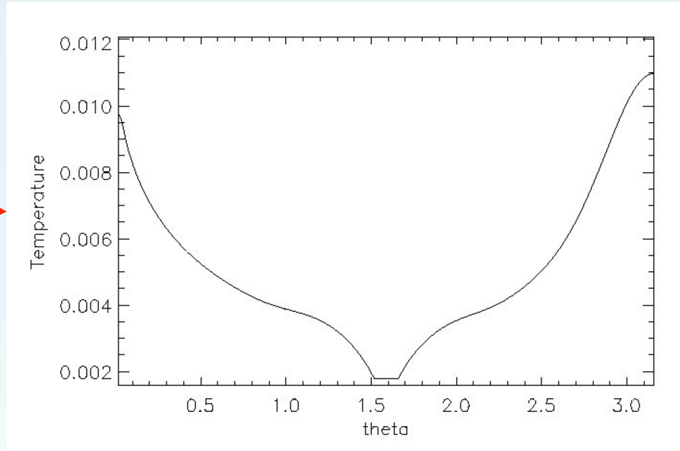


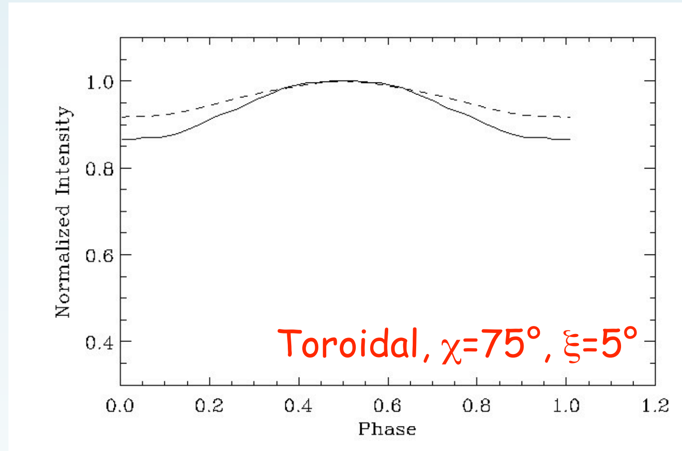
While radiative beaming is far less important for nearly aligned rotators..

B=6e12 G , T surface ~ 1.2 e6 K, Max of toroidal field at $x_{core} + \alpha\,(x_{crust} - x_{core})$

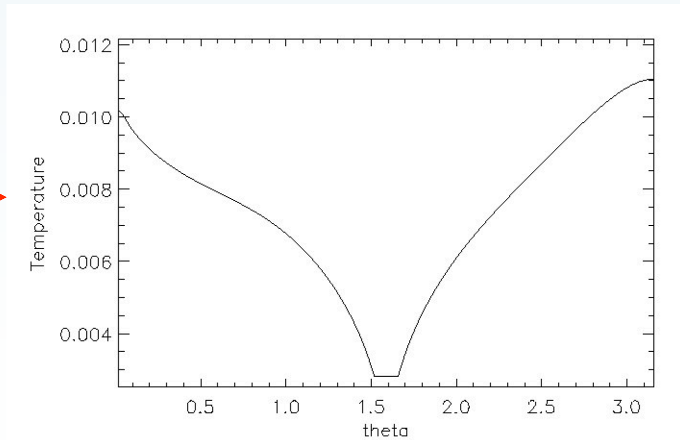
(Model as in Geppert at al, 2005)

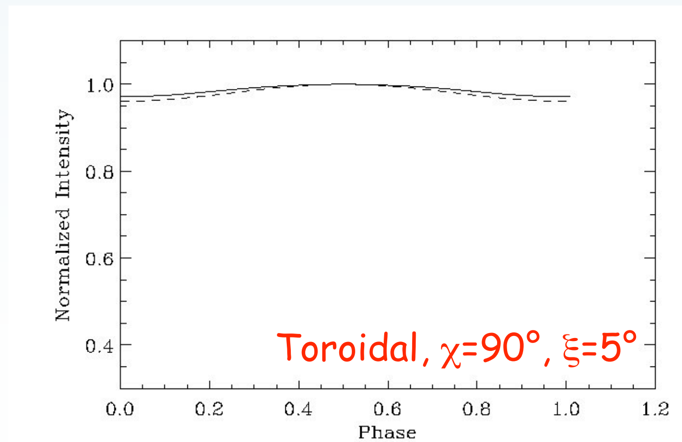
B^0_{crust} = 6e12 G
B^0_{core} = 10 G
B^0_{tor} = 1e15 G
α = 0.7





B^0_{crust} = 3e12 G
B^0_{core} = 3e12 G
B^0_{tor} = 1e15 G
α = 0.2





Conclusions:

- The magnetic field of XDINS is far more complicated than a core-centered dipole (Evidence for two spot non antipodal, skewness, PC analysis, etc)
- Possible reasons:
  a) Toroidal field in the crust (but dipole externally?)
  b) Quadrupolar components in the magnetosphere?
- In both cases values of B inferred from timing studies are not affected
- Case b: should imply a stronger variation of cyclotron/atomic lines with phase (possible spreading..)
- Case a: edges in the emission from the solid crust (Perez Azorin et al, 2006)
- Radiative beaming is crucial, in particular for nearly orthogonal rotators (as RBS1223?)
- Thermal map must be complex => deep observations spread over the spin cycle (and now precession cycle for 0720!) are crucial.