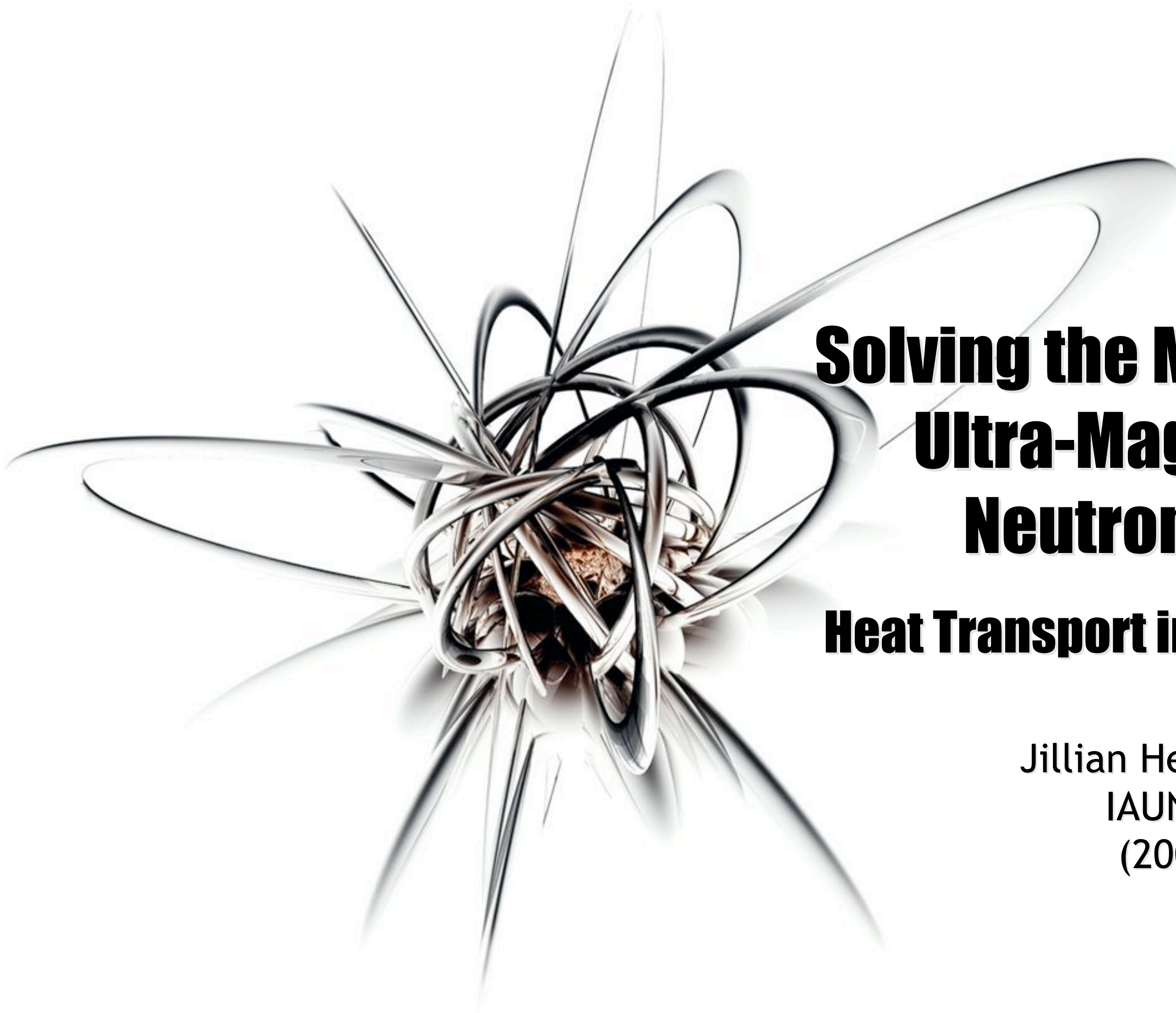


http://videa.deviantart.com/

Solving the Mysteries of Ultra-Magnetized Neutron Stars

Heat Transport inside the Crust

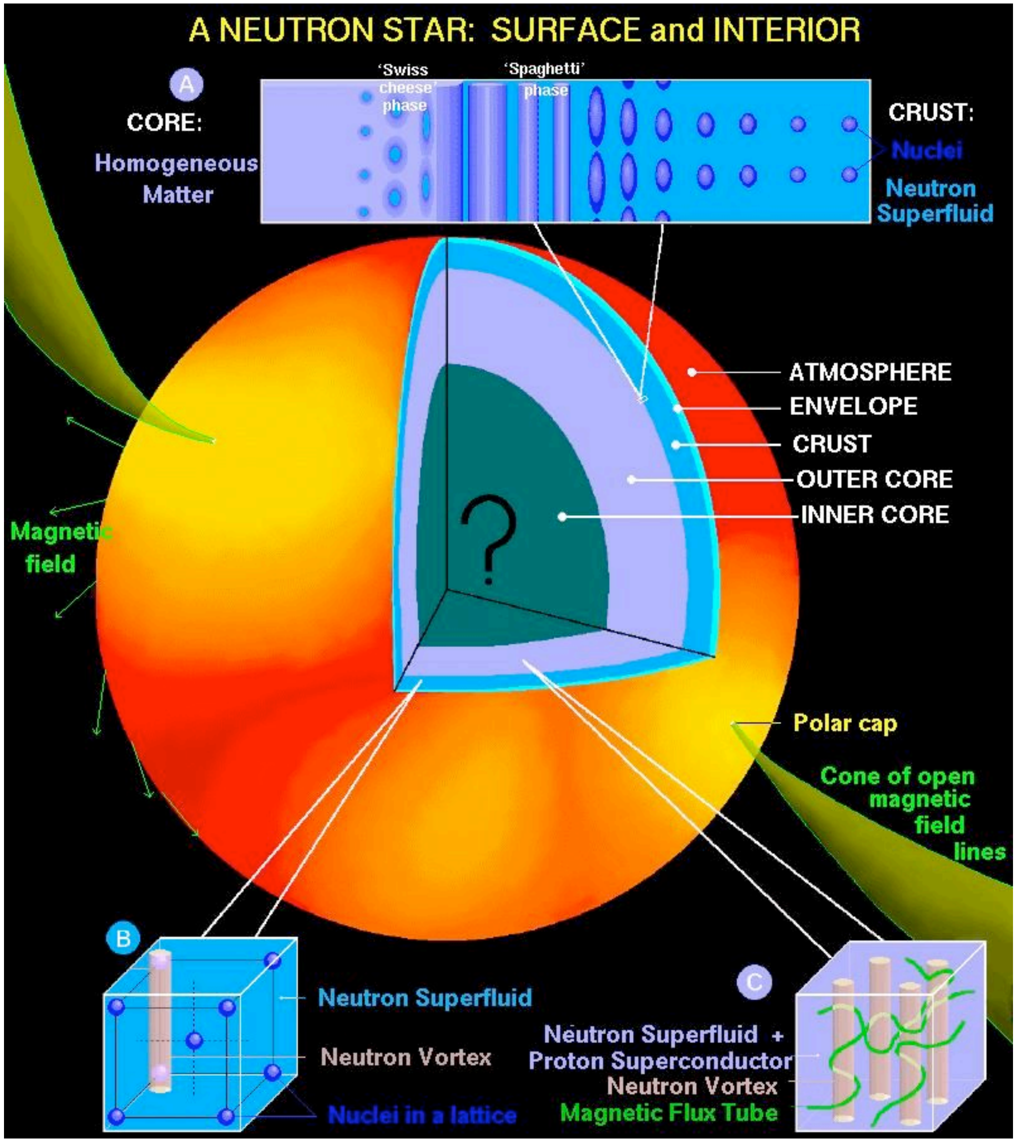
Jillian Henderson
IAUNAM

(2007)

Neutron Stars

<u>General characteristics:</u>

- masses between 1.1 and 2.1 M_{sol}
- corresponding radii between 20 – 10km
- central density ~ 10^{15} g cm^{-3}
- core: superfluid of degenerate neutrons + superconductor of degenerate protons
- inner core ?
- crust → envelope → atmosphere



Magnetic Breaking

Magnetic Dipole Model:

$$\dot{E} = -\frac{2}{3c^3} \mid \ddot{\mathrm{m}} \mid^2 = \frac{-B_p^2 R_{NS}^6 \Omega^4 \sin^2 \alpha}{6c^3}$$

Rotation Energy:

$$E = \frac{1}{2} I\Omega^2 \longrightarrow \dot{E} = I\Omega\dot{\Omega}$$

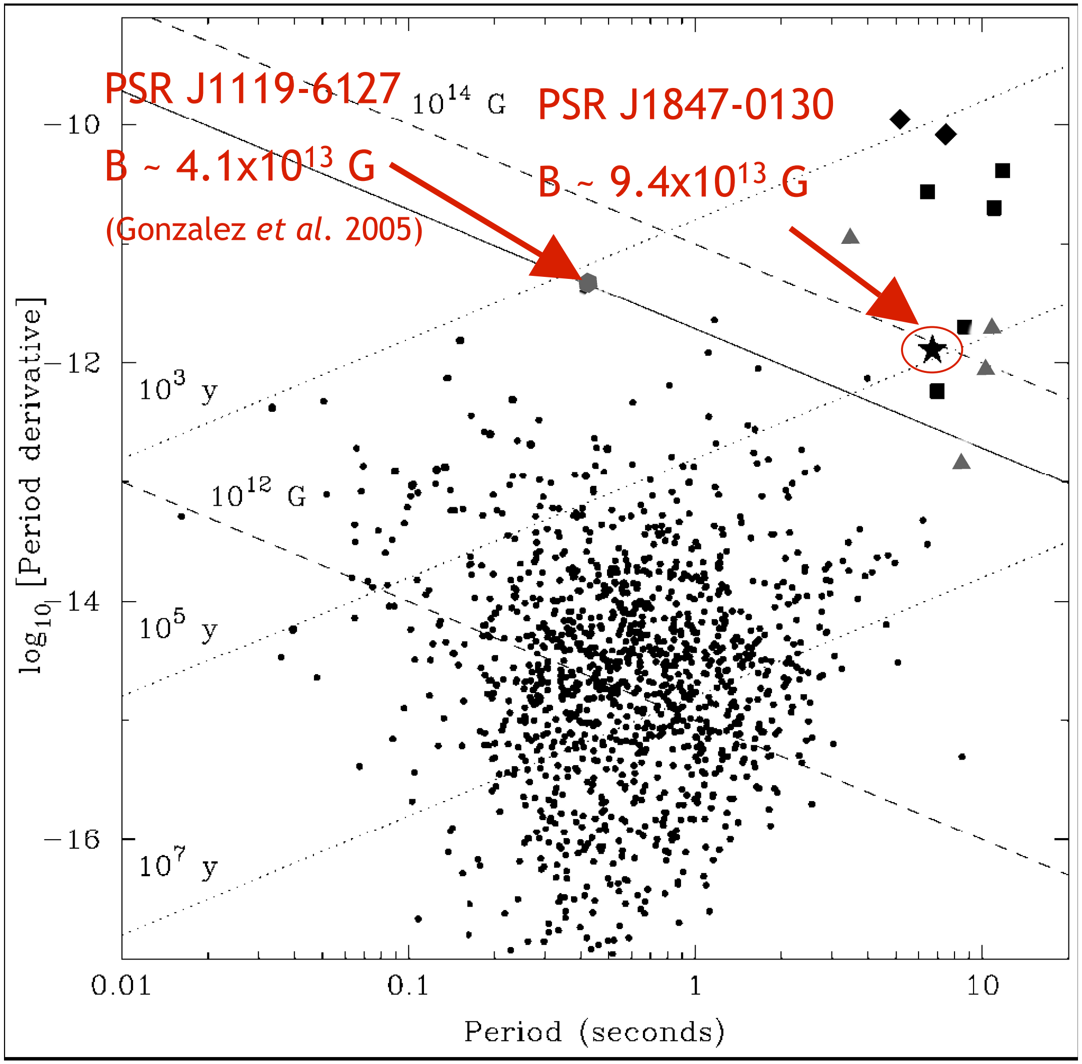
Compare the two:

$$B_p^2 \Omega^4 \propto \Omega\dot{\Omega}$$

Get the relations: $P = 2\pi/\Omega$ $\quad \dot{P} = -\dot{\Omega}/\Omega^2$

$$B \simeq 10^{12} \sqrt{P\dot{P}_{-15}} \mathrm{G}$$

Relation P – dP/dt



(McLaughlin *et al*. ApJ 591: L135. 2003. "PSR J1847-0130: A Radio Pulsar with Magnetar Spin Characteristics.")

HBPSR

("High Field Pulsars")

Critical quantum field:

$$B_{CR} \sim 4.4 \times 10^{13} G$$

Cyclotron energy = electron rest energy

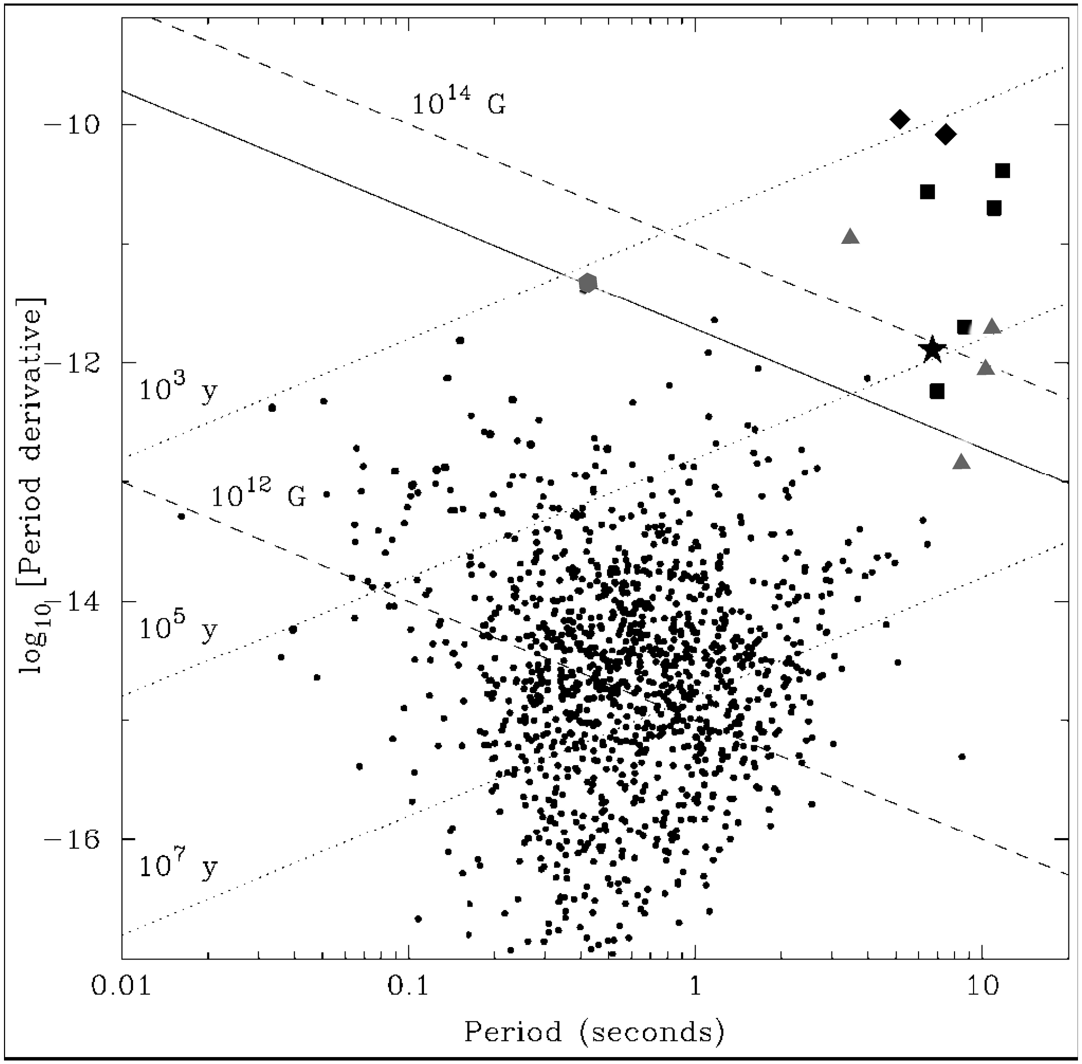
B > B_{CR} → "magnetic photon splitting" dominates "pair production" → no emission in the radio

Before the Parkes Multibeam Pulsar Survey (1999):

Largest inferred B ~ 2.1 x 10^{13}G for a radio pulsar.

AFTER: B ~ 1e13 - 1e14 G

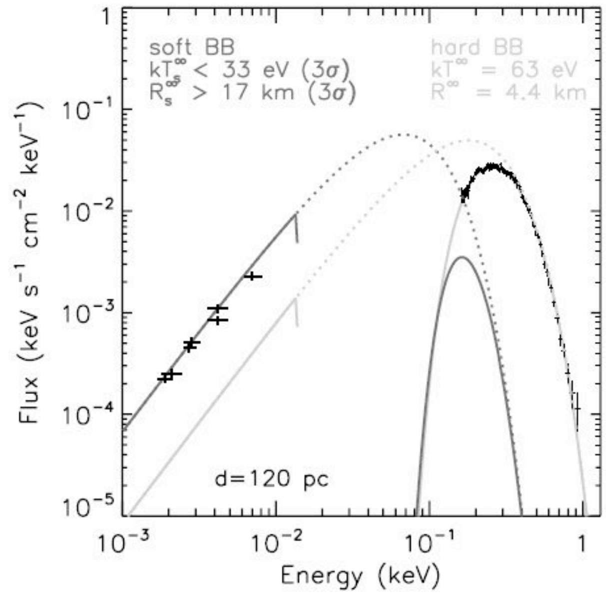
Relation P – dP/dt



(McLaughlin *et al*. ApJ 591: L135. 2003. “PSR J1847-0130: A Radio Pulsar with Magnetar Spin Characteristics.”)

XDINS

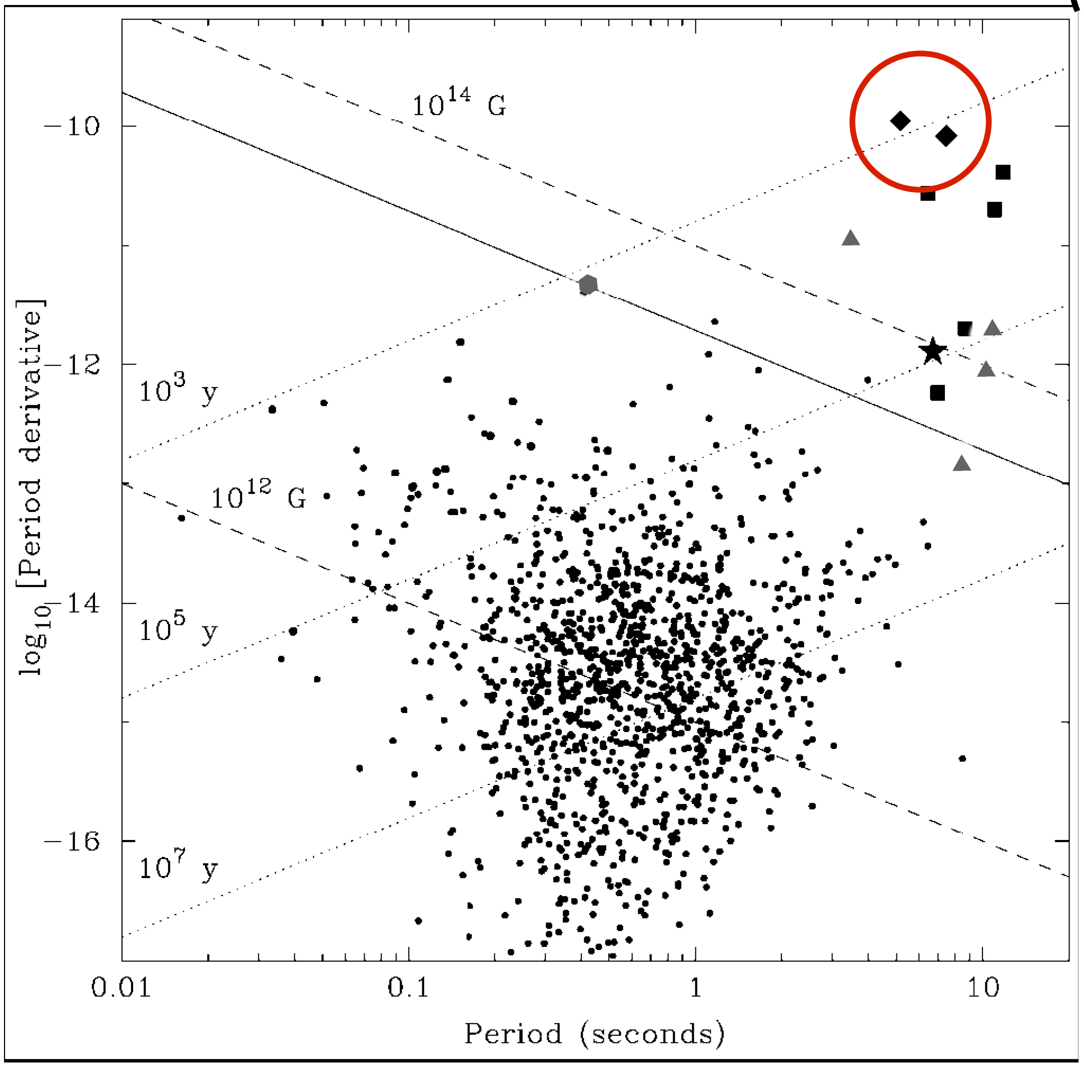
(“X-Ray Dim Isolated Neutron Stars”)



General Characteristics:

- low, but persistent emission in x-rays, $L_x \sim 10^{30}$-10^{31}ergs^{-1}
- no emission in the radio
- Black Body with kT ~ 40-110eV -> r = 3 - 5km
- broad absorption line -> proton cyclotron
- optical excess -> r > 10km
- pulsations in 6 sources -> B 10^13 - 10^14G
- 10^5 – 10^6 years old
- close, d ~ 100 – 300pc

Relation P – dP/dt



(McLaughlin *et al*. ApJ 591: L135. 2003. "PSR J1847-0130: A Radio Pulsar with Magnetar Spin Characteristics.")

SGRs

("Soft Gamma-Ray Repeaters")

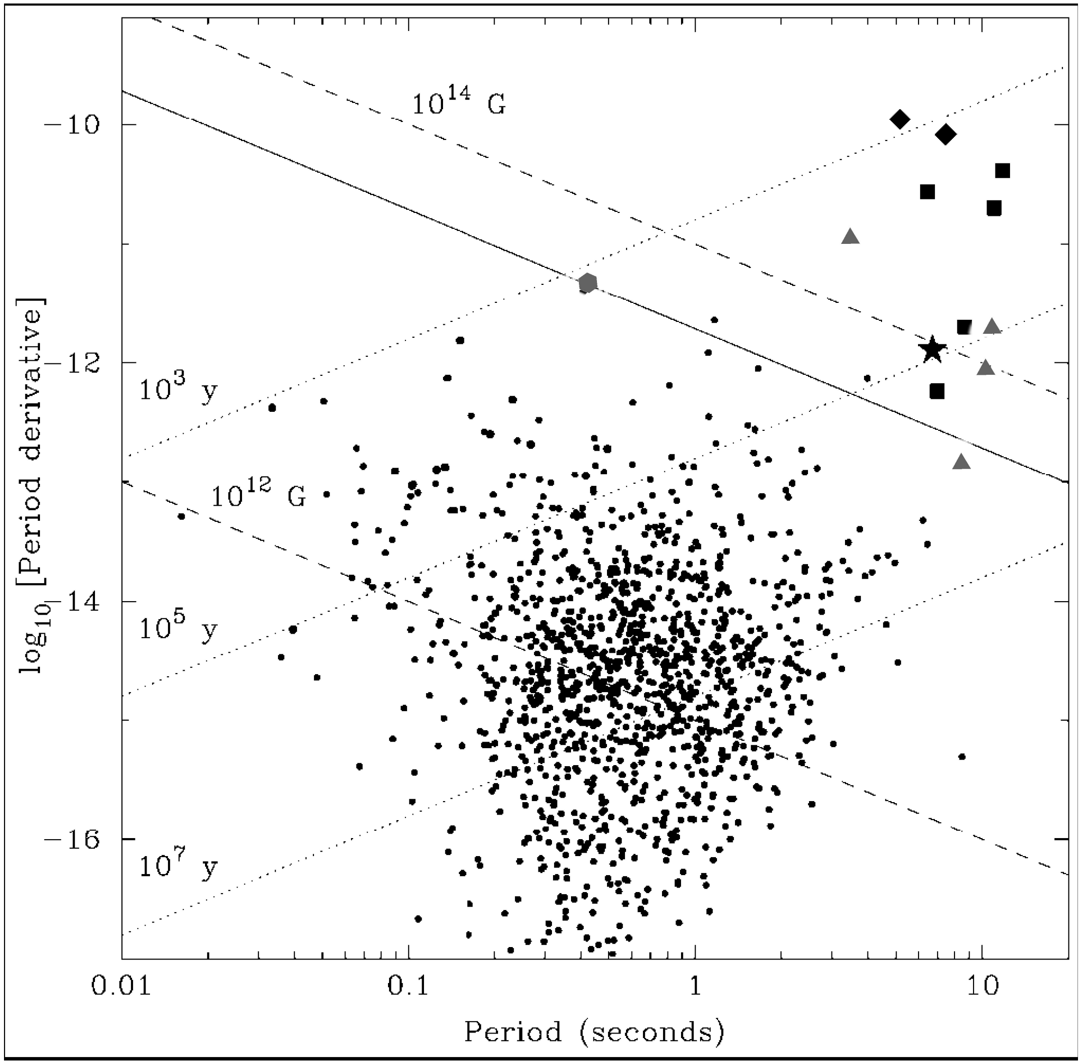
- short bursts (~100ms) en soft γ rays y x-rays with energies of ~10^{41}ergs and rise times of ~10ms
- 4 – (6?) in the Galactic and the LMC (1)
- optically thin Bremsstrahlung emission, kT~20-50keV

  \+ power law with n ~ 2-3 (quiescence)
- giant bursts, ~ $4\text{x}10^{44}$ erg (3)
- 3 sources with pulsations in quiescence → B ~ 10^{15} G

X-rays: surface origin

Bursts: crustal breaking and plasma excitation

Relation P – dP/dt



(McLaughlin *et al*. ApJ 591: L135. 2003. “PSR J1847-0130: A Radio Pulsar with Magnetar Spin Characteristics.”)

AXPs

(“Anomalous X-Ray Pulsars”)

- pulsations in x-rays, L_x ~ 10^{33} - 10^{35} ergs^{-1} , P ~ 6 – 12s
- Soft x-ray spectrum with (i) Black Body kT ~ 0.4keV y (ii) hard power law, n ~2.5 – 4
- Similar to the SGRs : wide profiles and P - dP/dt en quiescence
- Different to the SGRs: softer spectrum, less noisy, lower B, association with SN
- Bursts in 2 cases but with a correlation with the rotation
- “Anomalous” – X-ray pulsars: NS accreting from a massive companion, fluctuations in the emission, L_x ~10^{37} – 10^{38} ergs^{-1}
- lack of Doppler shift→ no companion
- associations with SNRs → young

Anisotropic Heat Transport:
magnetic field effects in the crust

Energy Balance:

$$C\frac{\partial T}{\partial t} = Sources - Sinks - \nabla \cdot \mathbf{F}$$

General reletivistic effects + heat transport:

$$e^{\Phi}\mathbf{F} = -\hat{\kappa} \cdot \nabla (e^{\Phi} T)$$

Anisotropic Heat Transport:
magnetic field effects in the crust

Thermal conductivity of the electrons

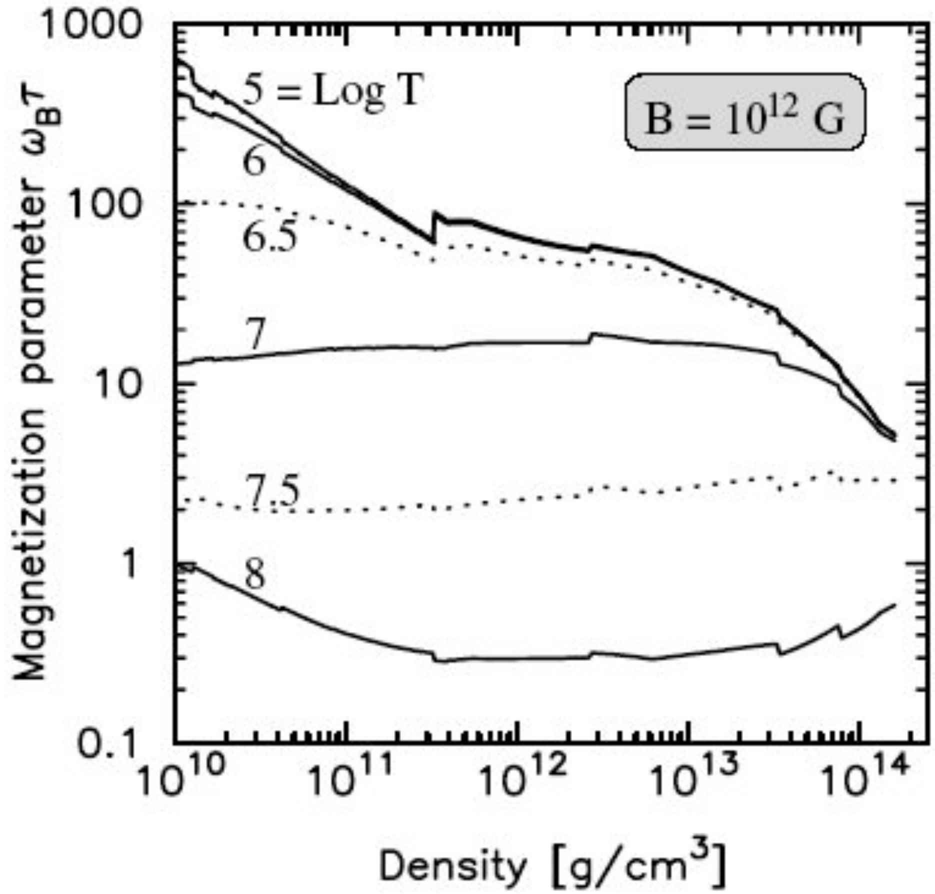
$$\overleftrightarrow{\kappa} = \begin{pmatrix} \kappa_{\parallel} & 0 & 0 \\ 0 & \kappa_{\perp} & \kappa_{\wedge} \\ 0 & -\kappa_{\wedge} & \kappa_{\perp} \end{pmatrix}$$

$$\kappa_{\parallel} = \kappa_0$$

$$\kappa_{\perp} = \frac{\kappa_0}{1+(\omega_B \tau)^2}$$

$$\kappa_{\wedge} = \frac{\kappa_0(\omega_B \tau)}{1+(\omega_B \tau)^2}$$

Electron gyrofrequency $\omega_B = \frac{eB}{m^* c}$



Surface Temperature Distribution With Magnetic Field:

Only considering the effect of the magnetic field in the envelope:

$$T_s^4(\Theta_B) = T_s^4(\Theta_B = 0)\sin^2\Theta_B + T_s^4(\Theta_B = 90)\cos^2\Theta_B$$

Greenstein & Hartke, 1983

Best present version: Potekhin & Yakovlev, 2001

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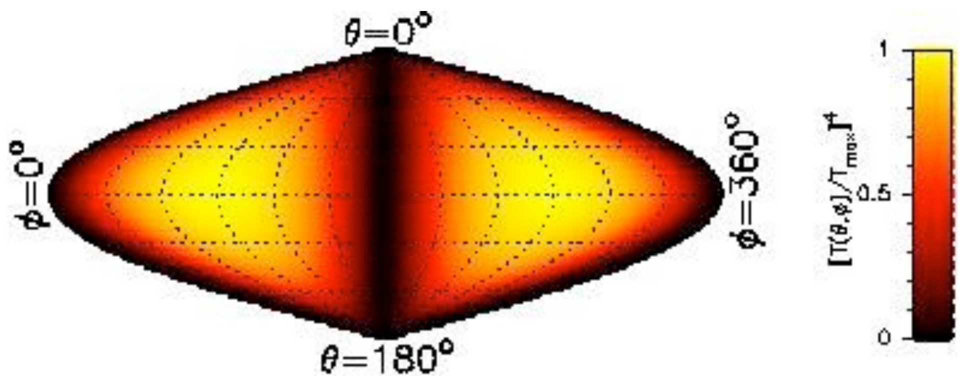
Puro Campo Dipolar



D. Page "*Surface temperature distribution in magnetized neutron stars. I. dipolar fields*", 1995

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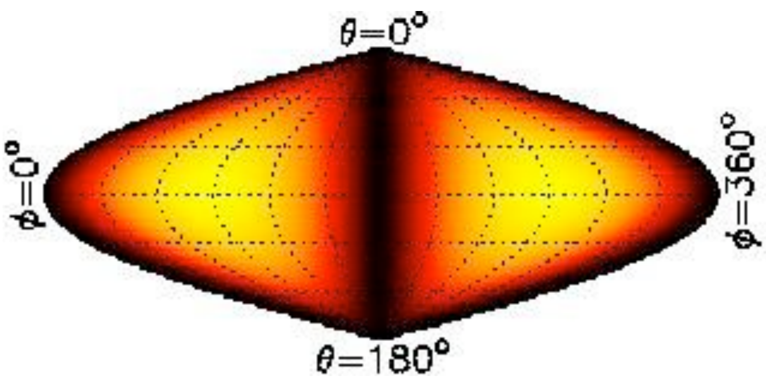
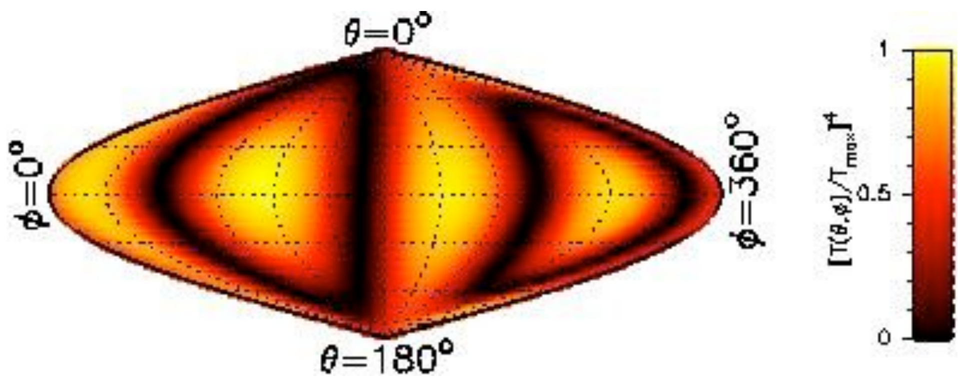
Purely Poloidal Dipolar



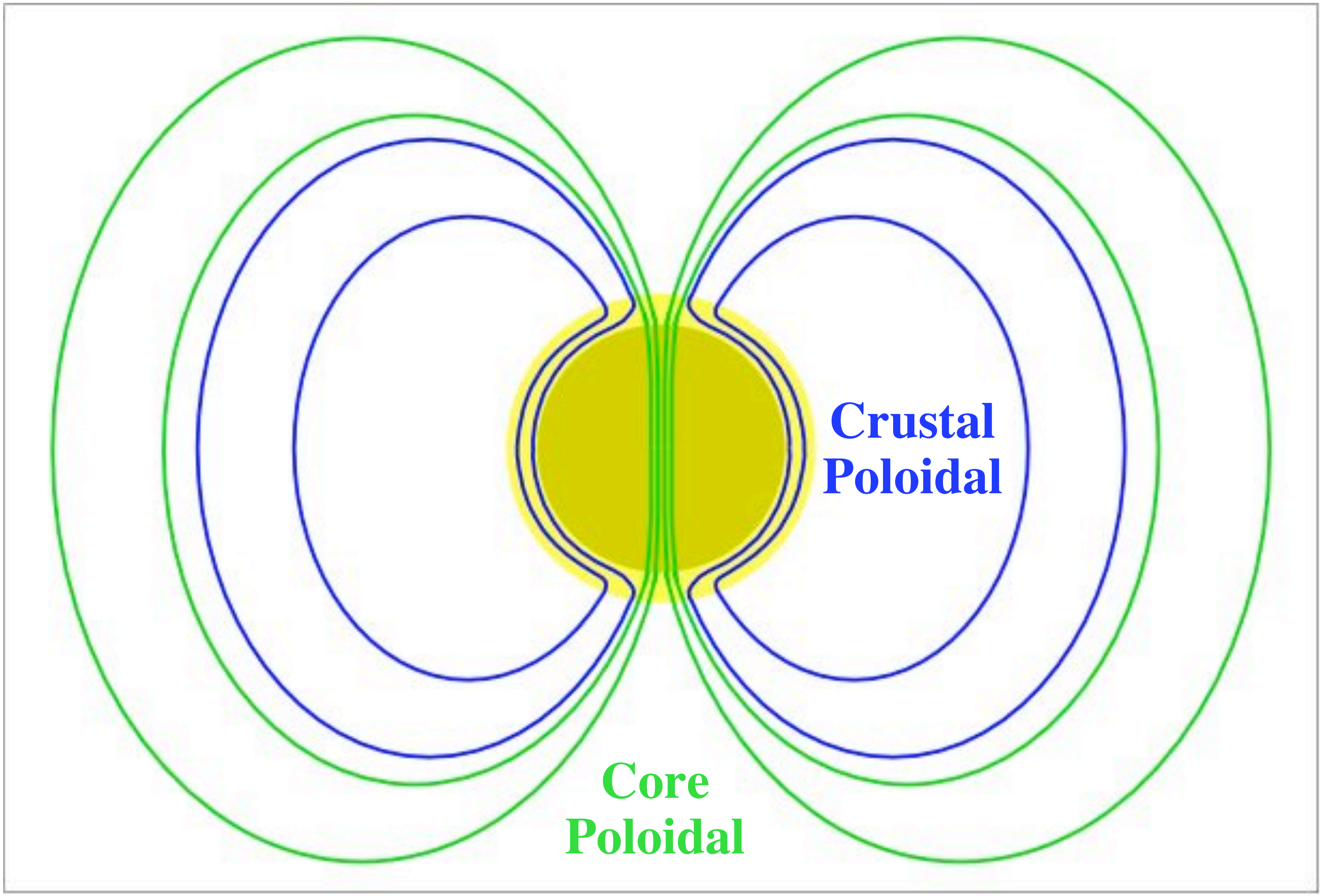
Poloidal Dipolar + Quadrupolar



D. Page "*Surface temperature distribution in magnetized neutron stars. I. dipolar fields*", 1995

D. Page & A. Sarmiento,"*Surface temperature distribution in magnetized neutron stars. II*" 1996

Dipolar Fields: Crust + Core Currents



Surface Temperature Distribution With Magnetic Field:

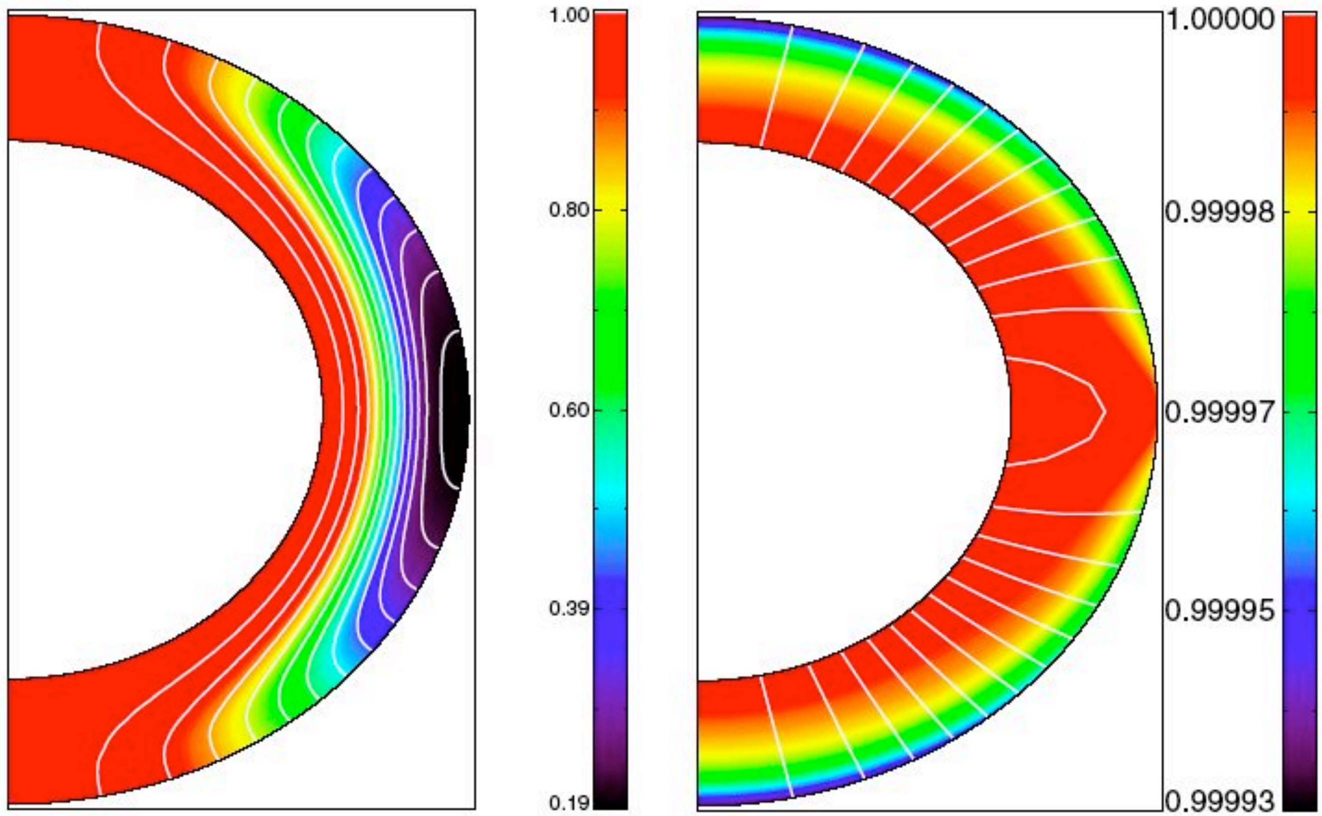
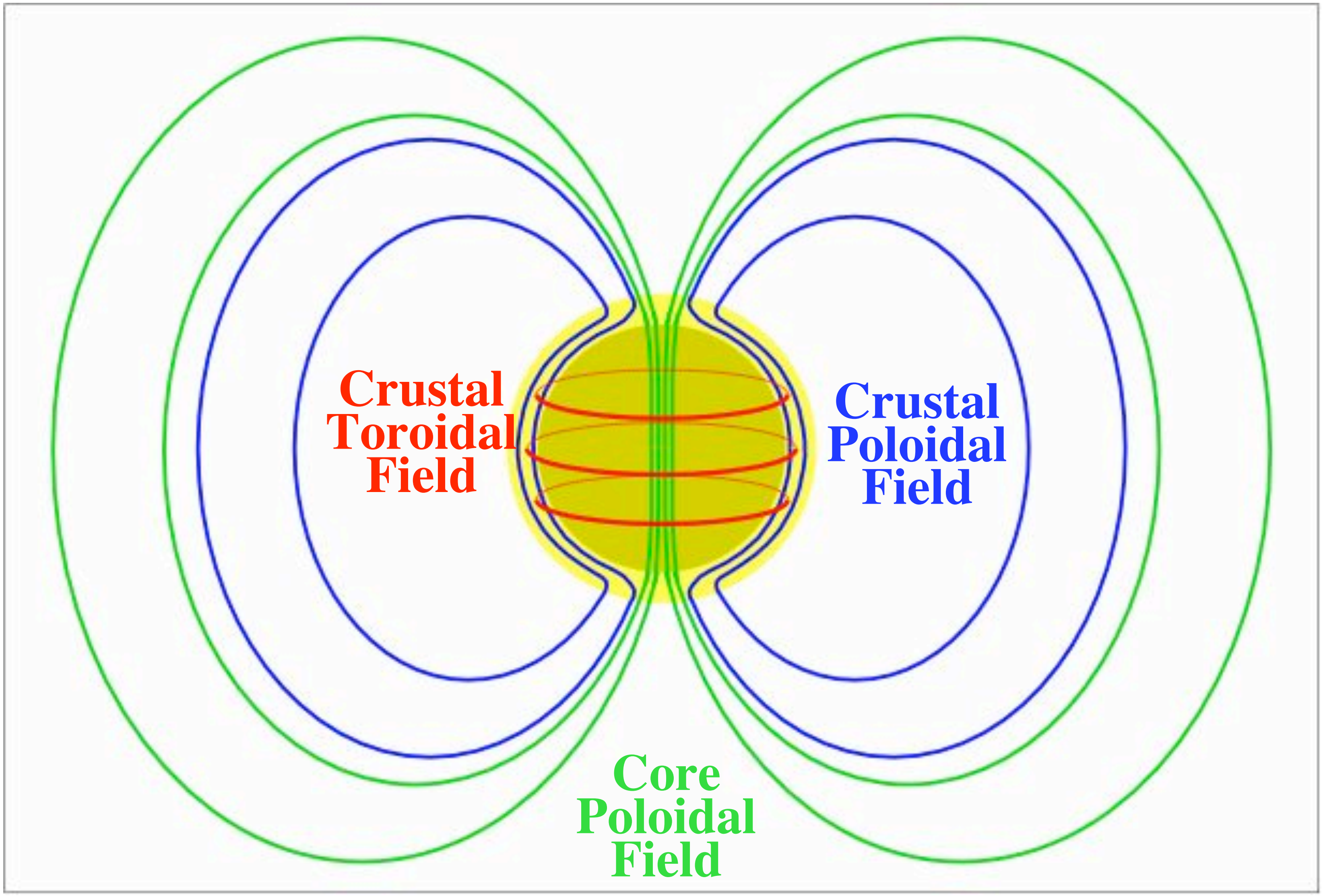


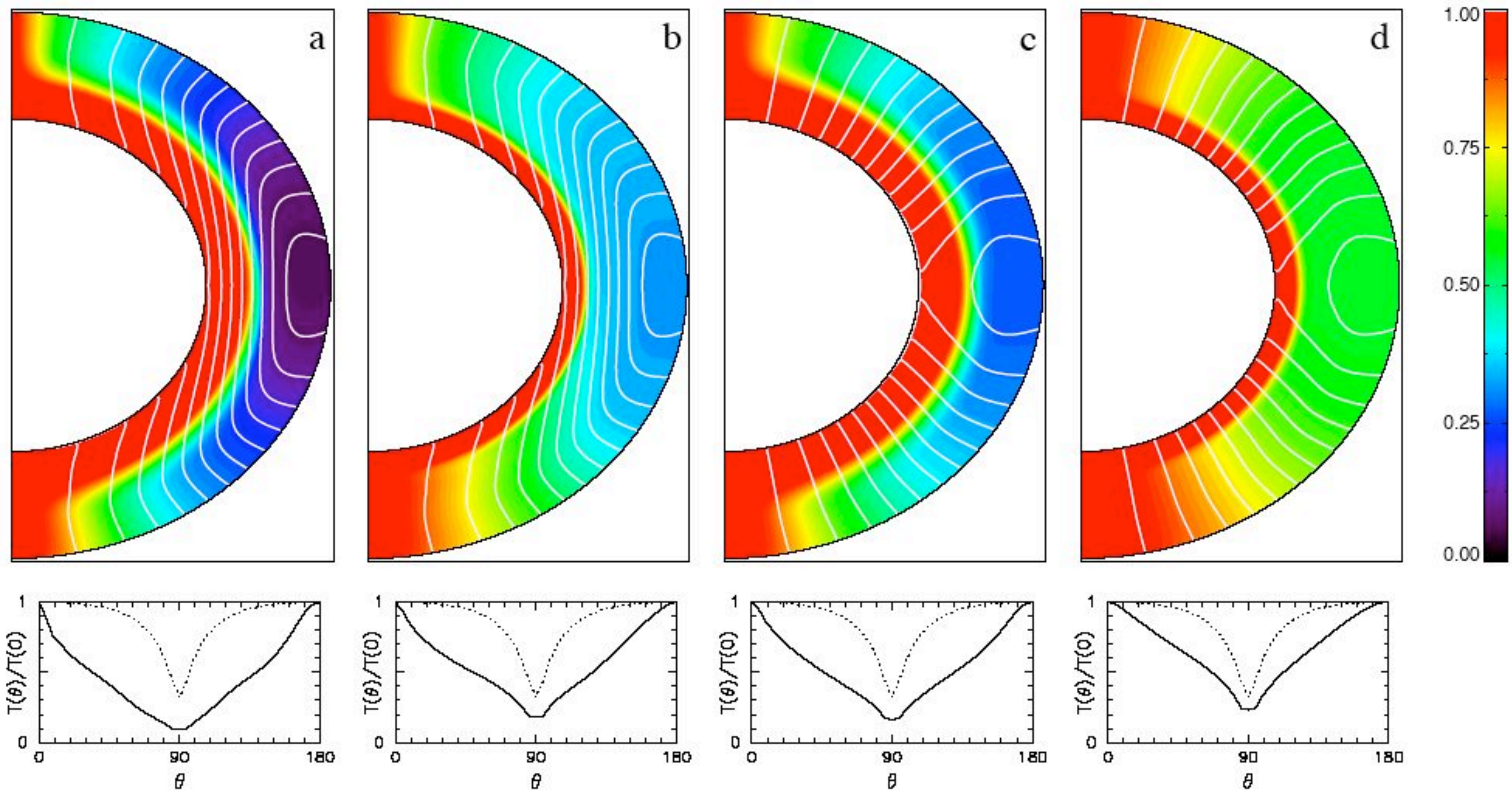
Fig. 7. Representation of both field lines and temperature distribution in the crust whose radial scale ($r(\rho_n) \leq r \leq r(\rho_b)$) is stretched by a factor of 5, assuming $B_0 = 3 \times 10^{12}$ G and $T_{core} = 10^6$ K. Left panel corresponds to a crustal field, right panel to a star-centered core field. Bars show the temperature scales in units of T_{core}.

Geppert, Kueker & Page, 2004

Poloidal + Toroidal Components

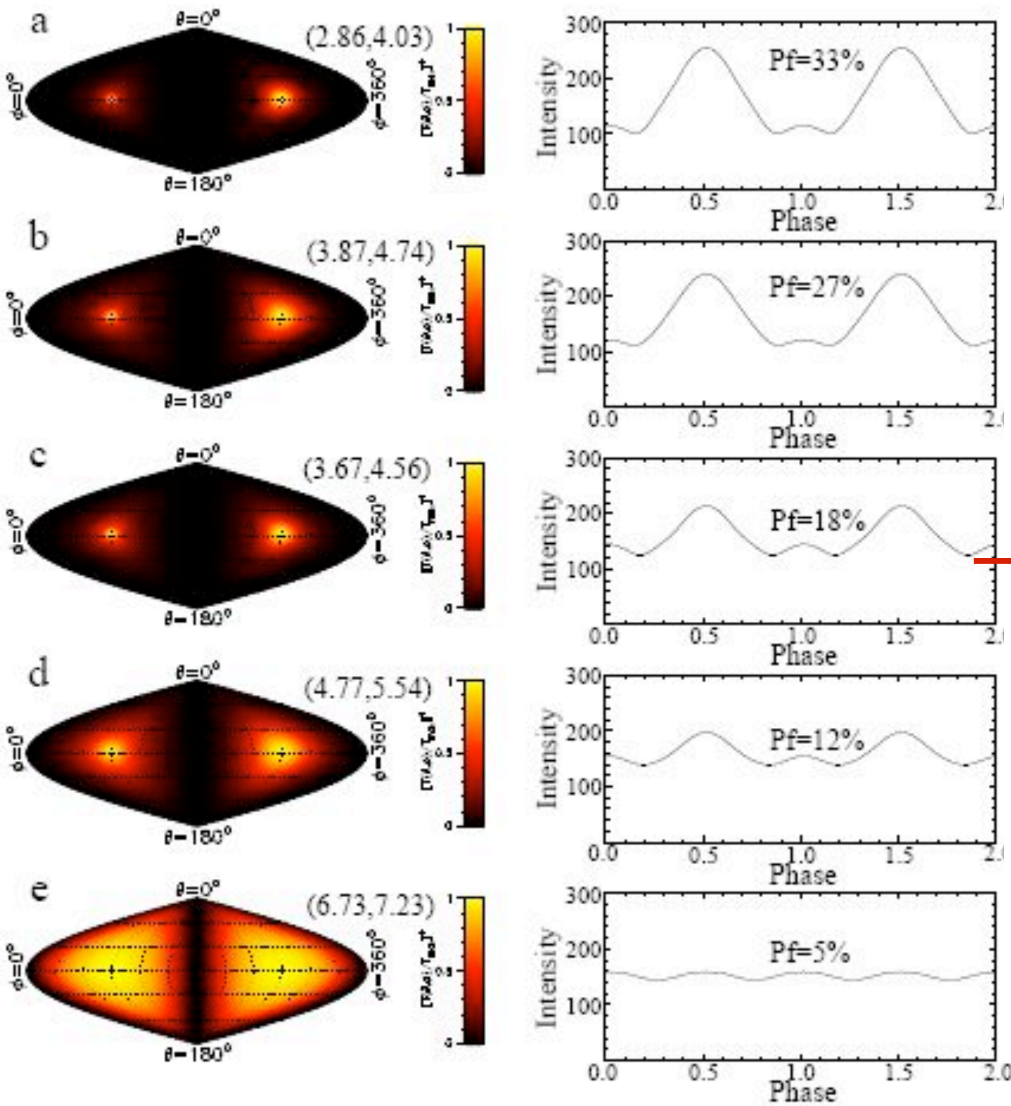


Surface Temperature Distribution With Magnetic Field:



Geppert, Kueker & Page, 2006

Surface Temperature Distribution With Magnetic Field:



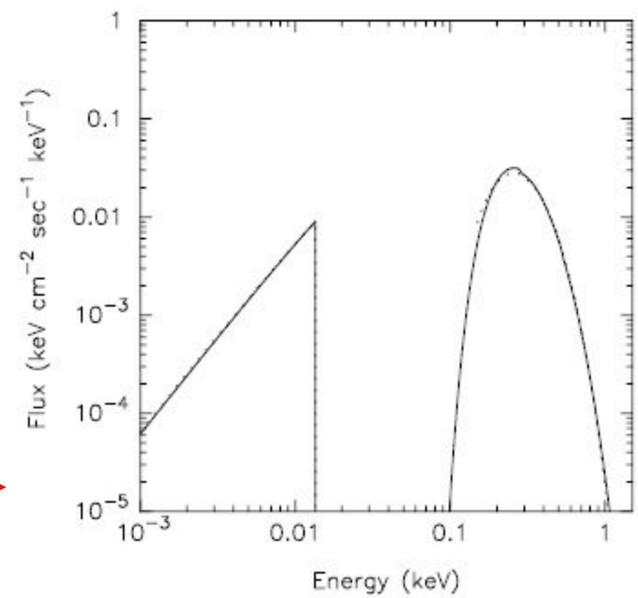
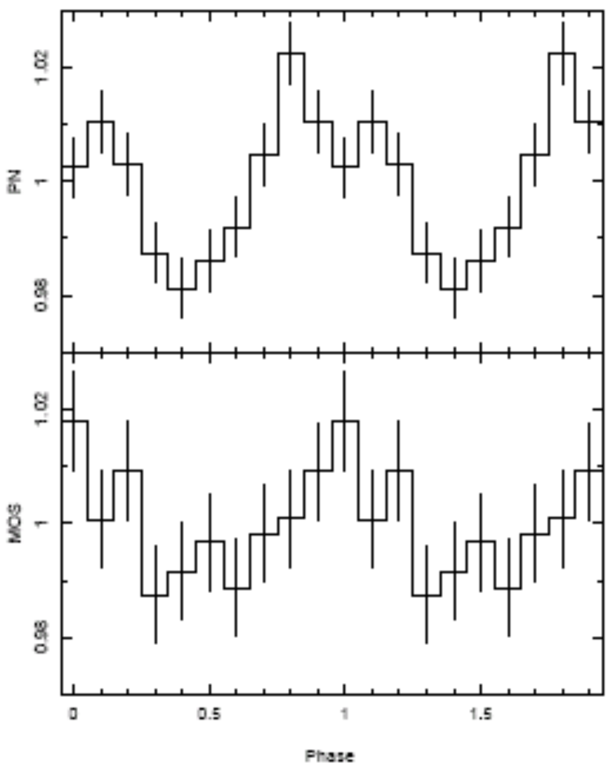


Fig. 10. Fit of the spectrum of RX J1856.5-3754. Dotted lines show the two blackbodies fit to the data from Trümper *et al.* (2004). The continuous line show our results: the star has a radius $R = 14.4$ km and $R_\infty = 17.06$ km for a 1.4 $M_\odot$, at a distance of 122 pcs ($N_H = 1.6 \times 10^{20}$ cm^{-2} for interstellar absorption) and the observer is assumed to be aligned with the rotation axis. The magnetic field structure corresponds to model c of Figure 6 adjusted to the 14.4 km radius with $T_b = 6.8 \times 10^7$ K, resulting in $T_{\rm eff}^\infty = 4.62 \times 10^5$ K and $T_{\rm max}^\infty = 8.54 \times 10^5$ K

Geppert, Kueker & Page, 2006

RX J1856.5-3754: new observations

<u>Observations:</u> *Tiengo & Mereghetti, 2007, ApJ 657:L101-L104, "XMM-Newton Discovery of 7s Pulsations in the Isolated Neutron Star RX J1856.5-3754."*



P = 7.05514 +/- 0.00007s

Pdot < 1.9e-12 s/s

B < 1.2e14G

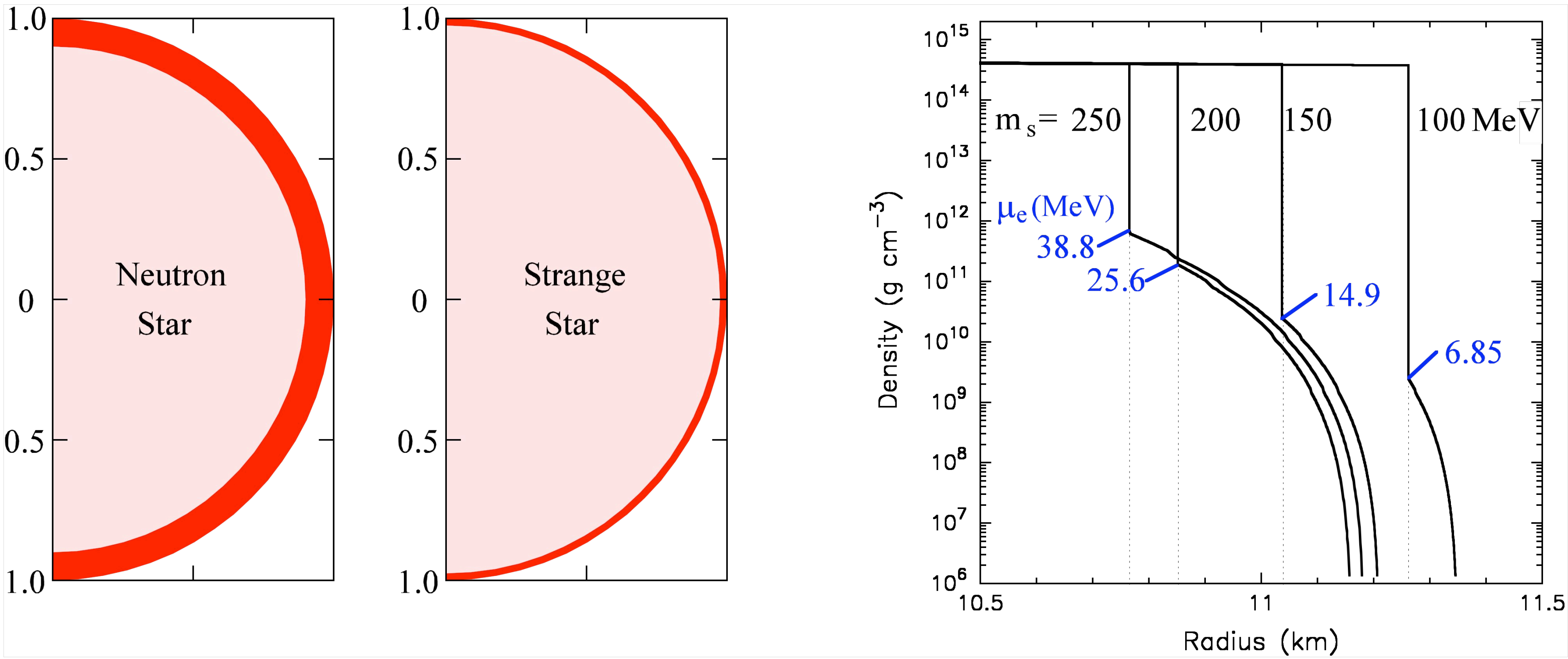
T > 6e4 years

<u>PF = 1.6% +/- 0.2%</u>

α = 90° → PF ~ 18% previous model

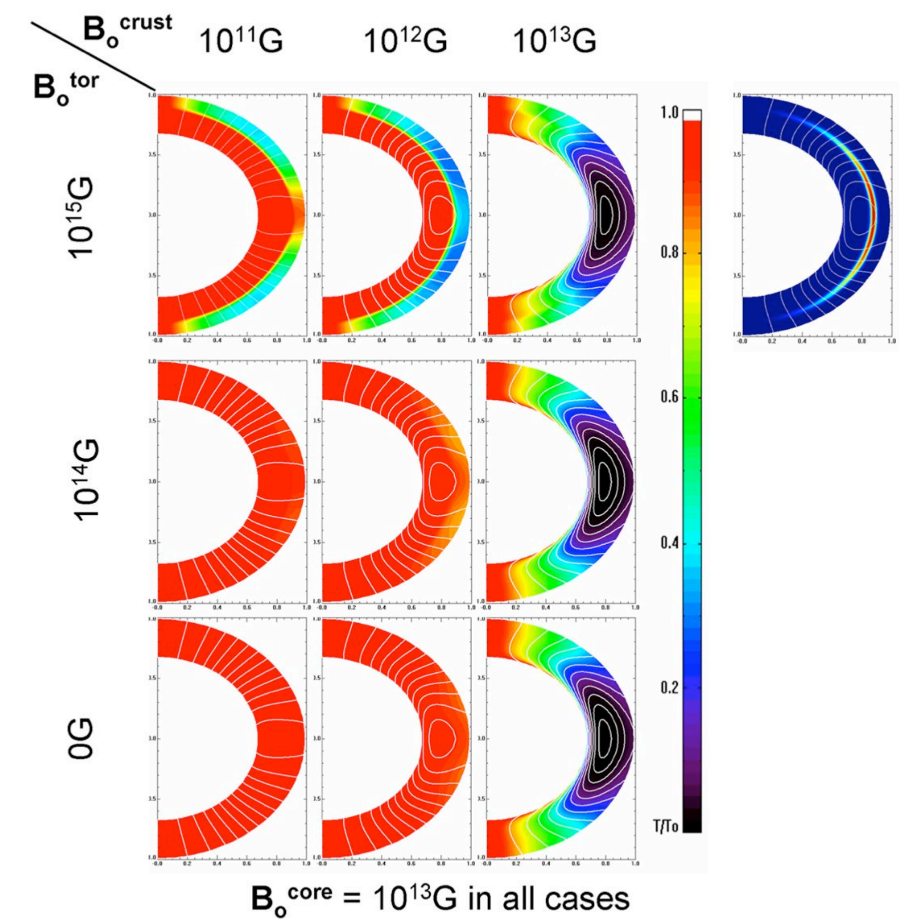
α = 8° → PF ~ 1.5%

RX J1856.5-3754: Quark Star?



(Henderson & Page. *2007. Ap&SS.tmp*. “RX J1856.5-3754 as a Possible Strange Star Candidate.”)

RX J1856.5-3754: Quark Star?



B_{tor} = 1e15 G

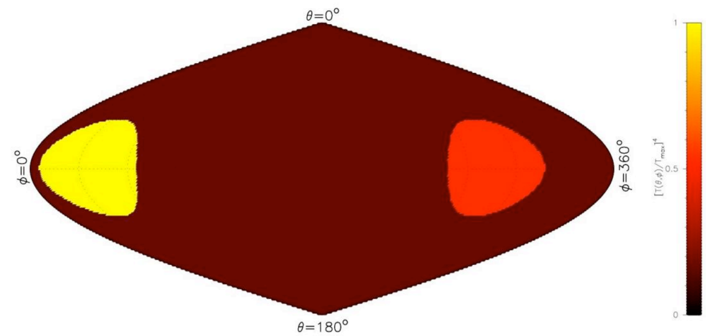
Δr = 250 m

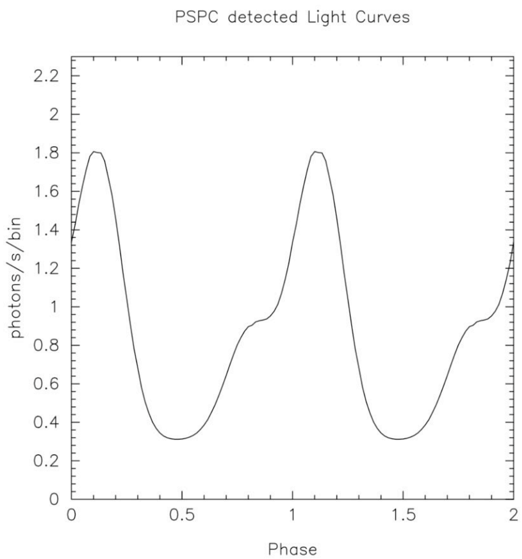
But the magnetic sheer stress ($B_r B_\theta$ / 4π) is too large for such a thin layer

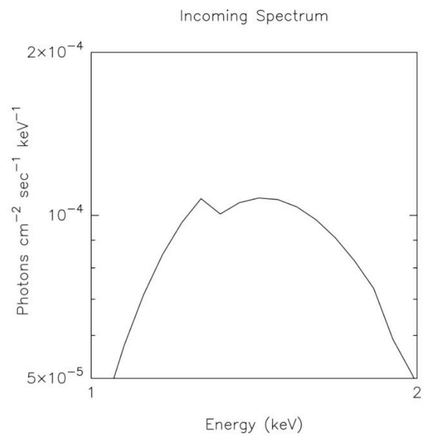
→ NOT PROBABLE

(Henderson & Page. *2007. Ap&SS.tmp*. "RX J1856.5-3754 as a Possible Strange Star Candidate.")

PSR J1119-6127:
High Field Pulsar





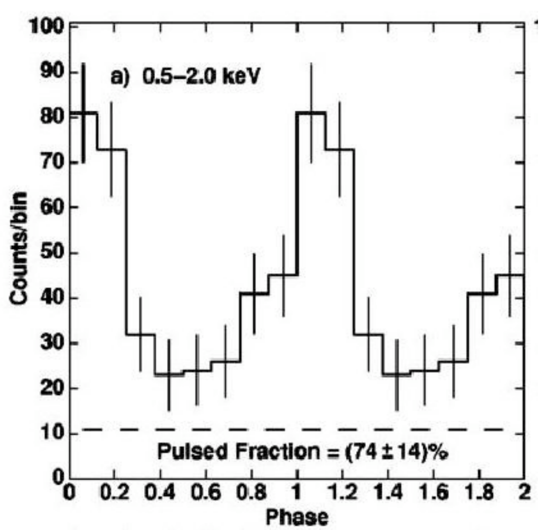


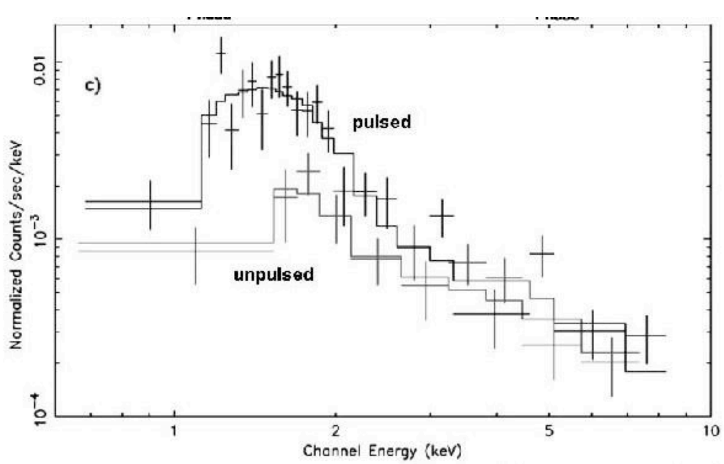
Model:

T1 = 3.6e6K

T2 = 4.2e6K **α = 90° → PF ~ 68%**

Ts = 2.7e6K





Observations:

P = 0.408s

t = 1700 years

B = 4.1e13 G

Tbb,∞ = 2.4e6 K

PF = (74 +/- 14) %

(Gonzalez *et al*. Ap&SS tmp 2007. "PSR J1119-6127 and the X-Ray Emission from High Magnetic Field Radio Pulsars.")