Observable Pulsed Fractions of Thermal Emission from Neutron Stars with Toroidal Magnetic Fields

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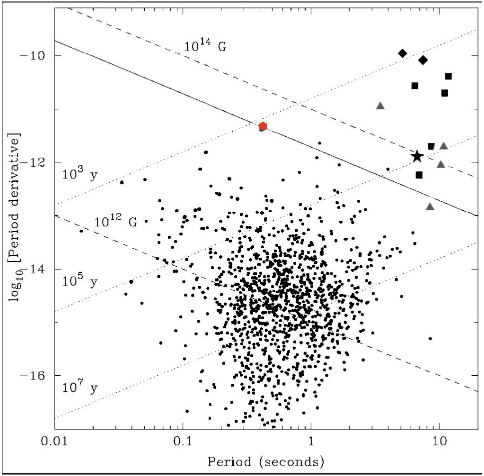
The Physics of Neutron Stars, St.Petersburg, 2008

Motivation

To hunt for possible explanations to puzzling observations:

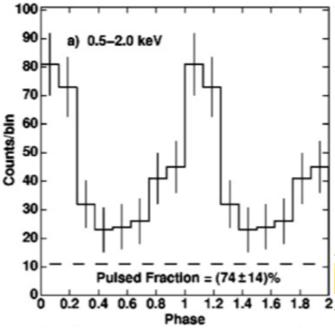


PSR J1119-6127

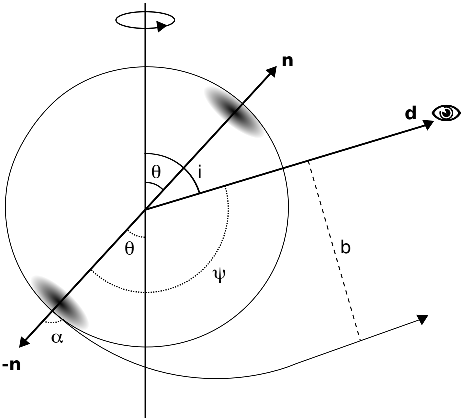
(Gonzalez et al. 2005)

$\rightarrow B \sim 4.1 \cdot 10^{13} G$

$\rightarrow PF \sim 74 \pm 14\%$



Theory - Observed Flux
Beloborodov (2002)



Inclination: $\mu = \mathbf{n} \cdot \mathbf{d}$, $\bar{\mu} = \bar{\mathbf{n}} \cdot \mathbf{d}$

The spot inclinations will vary in time, $\mu = \mu(t)$, between $\mu_{min} = \cos(i + \theta)$ and $\mu_{max} = \cos(i - \theta)$.

The visible part of the star is defined by a circle $\mu = \cos\psi$.

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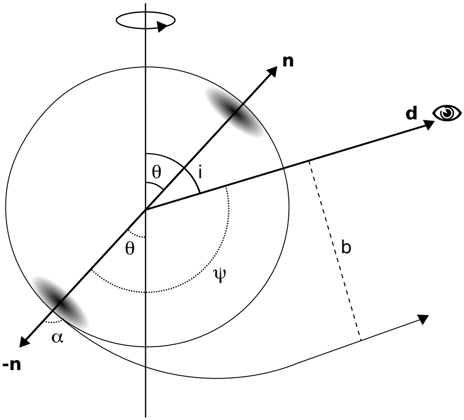
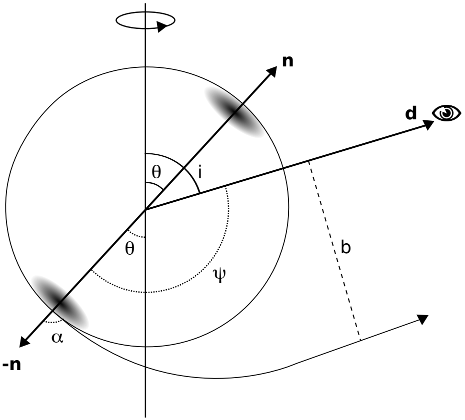


Curved spacetime:

$$1 - \cos\alpha = (1 - \cos\psi)\left(1 - \frac{r_g}{R}\right)$$

$$dF = \left(1 - \frac{r_g}{R}\right)^2 I_o(\alpha)\cos\alpha \frac{dS}{D^2}$$

Theory - Observed Flux
Beloborodov (2002)



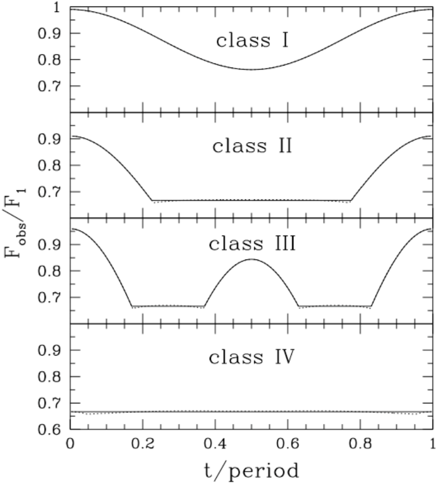
$$\frac{F}{F_1} = \mu\left(1 - \frac{r_g}{R}\right) + \frac{r_g}{R}$$

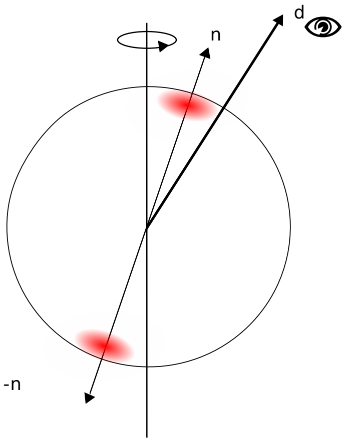
$$\frac{\bar{F}}{F_1} = -\mu\left(1 - \frac{r_g}{R}\right) + \frac{r_g}{R}$$

Pulsed Fraction (PF):
$PF =$
$(F_{max} - F_{min})/(F_{max} + F_{min})$

Theory - Class I Lights Curves
Beloborodov (2002)

$$PF = \frac{(\mu_{max} - \mu_{min})}{(\mu_{max} + \mu_{min} - 2\mu_v)}$$

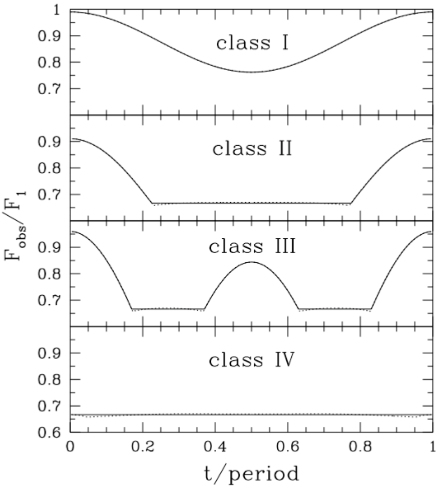


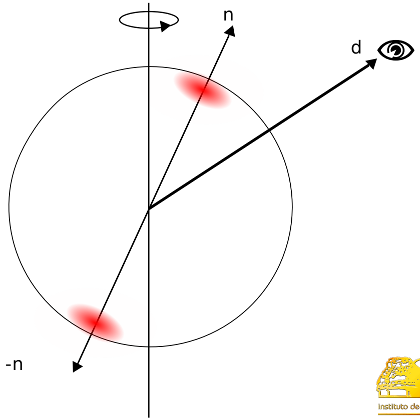


Theory - Class II Lights Curves

Beloborodov (2002)

$$PF = \frac{(\mu_{max} + \mu_v)}{(\mu_{max} - 3\mu_v)}$$

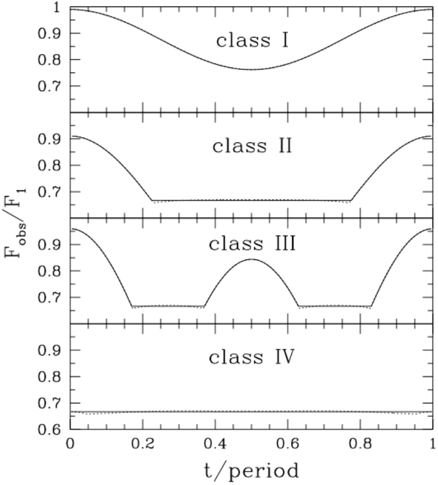


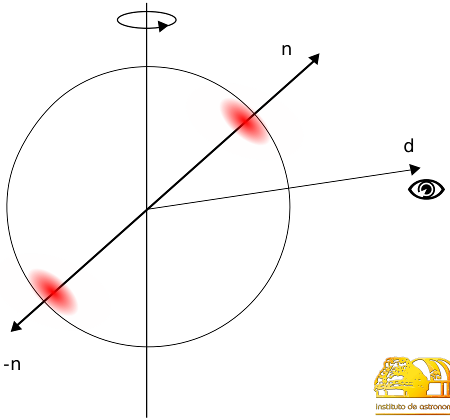


Theory - Class III Lights Curves

Beloborodov (2002)

$$PF = \frac{(\mu_{max} + \mu_v)}{(\mu_{max} - 3\mu_v)}$$

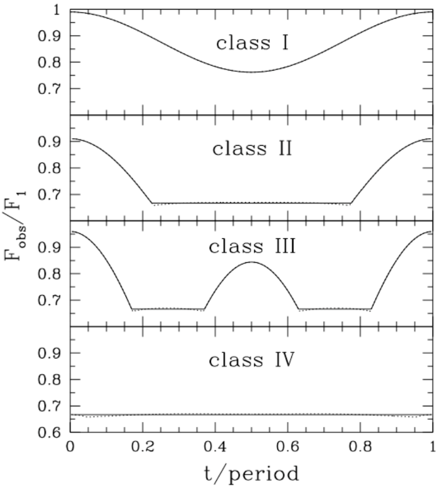


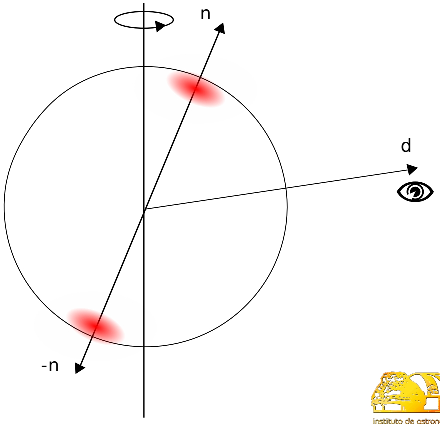


Theory - Class IV Lights Curves

Beloborodov (2002)

$PF = 0$





Magnetic Field Effects
“Beaming”

$$dF = \left(1 - \frac{r_g}{R}\right)^2 I_o(\alpha)(\cos\alpha)^{BF+1} \frac{dS}{D^2}$$

$$\mu_v \longrightarrow \frac{-(r_g/R)^{BF+1}}{1-(r_g/R)^{BF+1}}$$

$$PF_{max} \longrightarrow \frac{1-2(r_g/R)^{BF+1}}{1+2(r_g/R)^{BF+1}}$$

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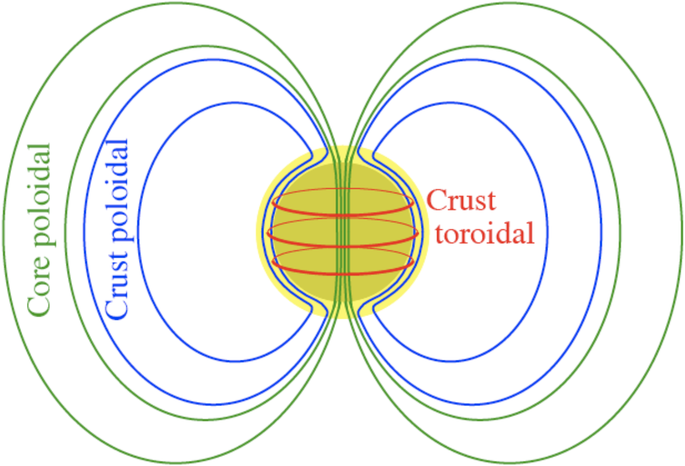
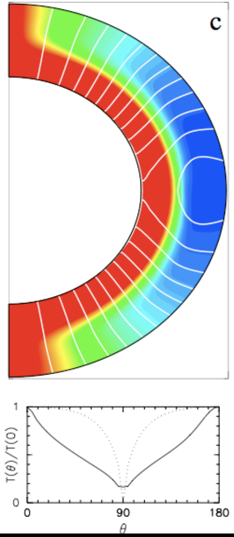
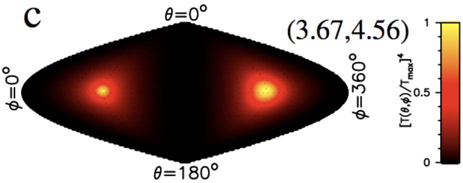
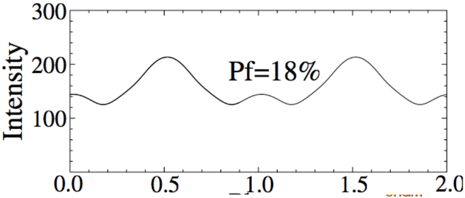
Magnetic Field: Crust



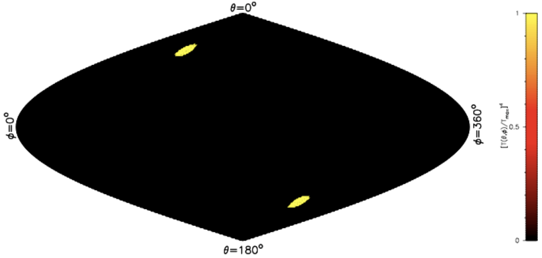
Magnetic Field
Geppert, Küker & Page, 2006







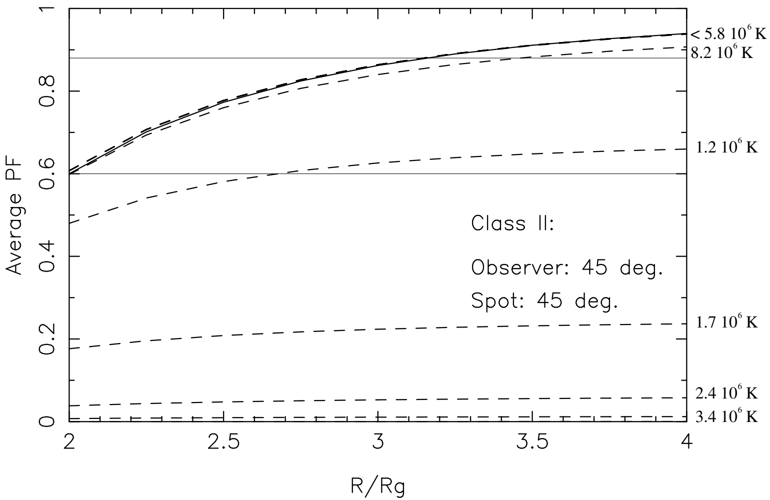
Numerical Model
Page (1995)



$T_{sp} = 5 \cdot 10^6 K$
$(\theta, i) = (45, 45), (30, 60), (60, 80)$
$diam = 10, 30, 50$
$2 \leqslant R/r_g \geqslant 4$
$BF = 0, 1, 2$

Results

Effect of surface temperature gradient



Results
Antipodal hot spots

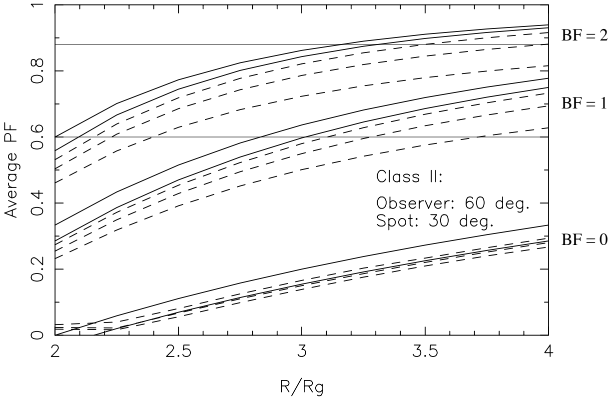
PSR J1119–6127

upper bound

lower bound

Spot Diameter:

– 10 deg.
– 30 deg.
– 50 deg.



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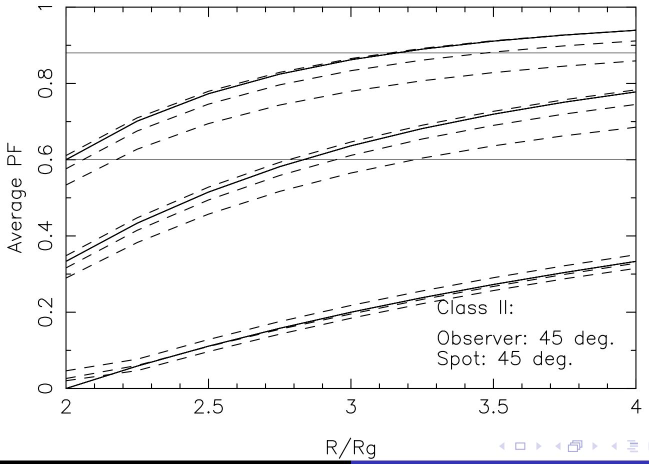
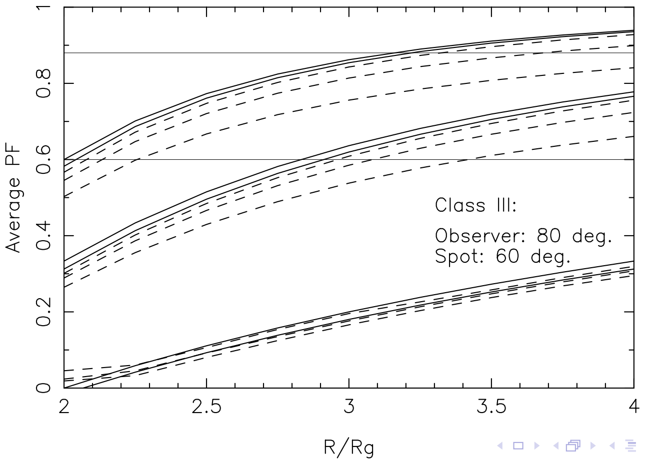
Antipodal hot spots

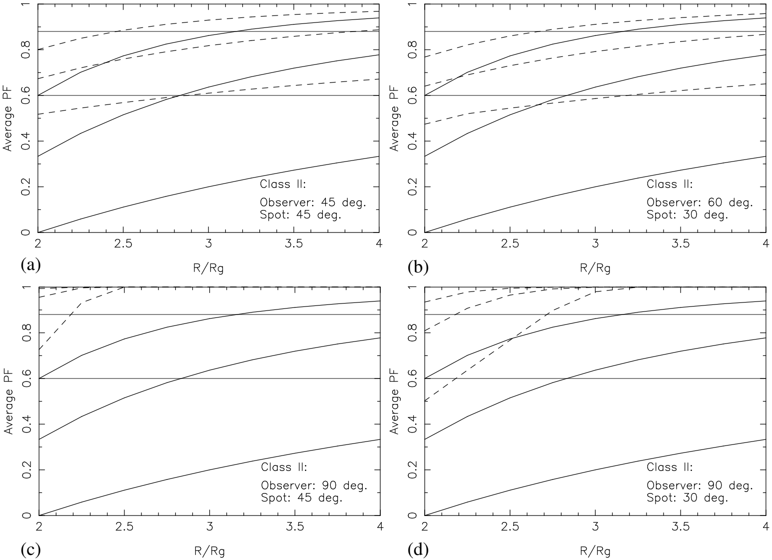


Results

Antipodal hot spots

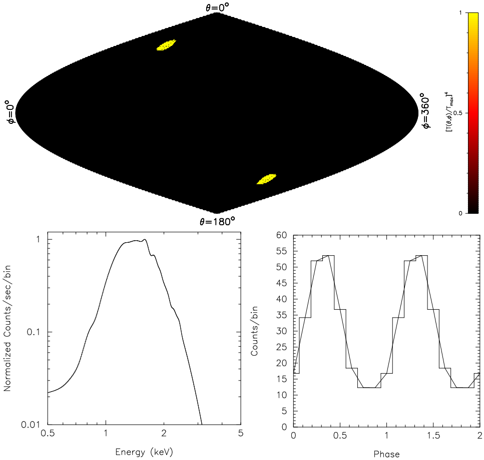


Results: Non-antipodal hot spots



Results

Simulated spectrum and light curve



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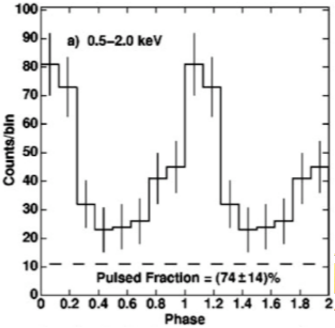

Summary

- small spot diameter
- some beaming required
- relative temperature between spot and main surface makes no difference to the PF after $\sim$ order of magnitude
- cooling neutron star with toroidal field can produce these small, intense hot spots

- Outlook
  - 2D, 3D cooling simulations to get the inhomogenous surface temperature of the star and “play” with hot spot size
  - BETTER / MORE OBSERVATIONS!!!
  - possibly include more realistic beaming scenarios (Zavlin et al. 1995).

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