Gamma-ray emission in the pulsar striped wind scenario

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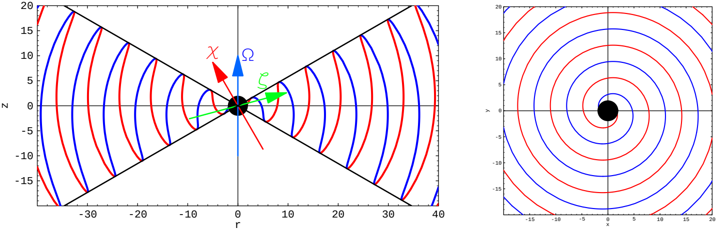
Workshop Gamma-ray variability - Heidelberg - 3/12/2010

Outline

The striped wind structure

Asymptotic MHD solution : oblique rotator (Bogovalov 1999)



- Ω : rotation axis
- χ : inclination of magnetic axis
- ζ : inclination of line of sight.

Properties

- assumes only a B_φ component decreasing like $1/r$
- an exact analytical expression for B_φ is known
- independent of the magnetospheric structure inside the light cylinder
- discontinuous magnetic polarity reversal $\Rightarrow$ infinitely thin current sheets (more realistic model would include finite thickness)

High-energy emission from isolated/binary pulsars

1. What ? objectives

   Explain the high-energy pulsed emission (>10 MeV) and spectral variability of several gamma-ray pulsars.

2. How ? Inverse Compton emission

   target photons

   - cosmic microwave background, CMB
   - synchrotron photons from the nebula, X-ray
   - thermal emission from the neutron star surface, black body with $T_{\rm bb} \approx 10^6$ K
   - photons from companion star

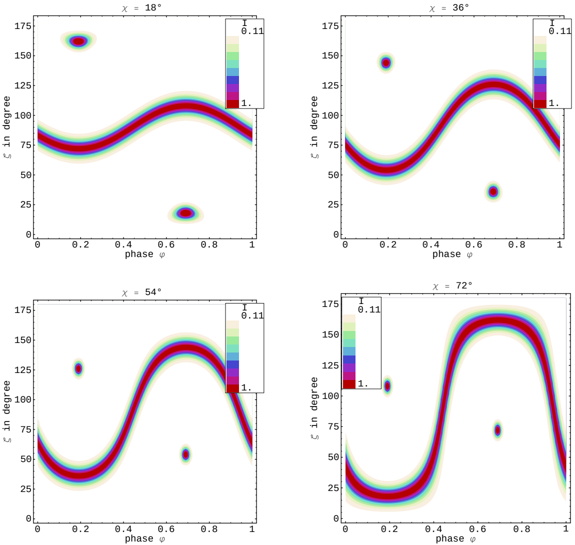
3. To whom ? applications

   ultra-relativistic electrons in the current sheets scattering of

   - the cosmic microwave background photons
     application to Geminga
   - the thermal X-ray photons
     application to Vela, $L_X = 10^{26}$ W, $\epsilon_\gamma \approx 1$ keV
   - companion star
     application to PSR B1259-63

4. link to other wavelengths ? pulsed radio ?

Relation between radio and gamma-ray pulses



(Pétri (2010) MNRAS, in press)

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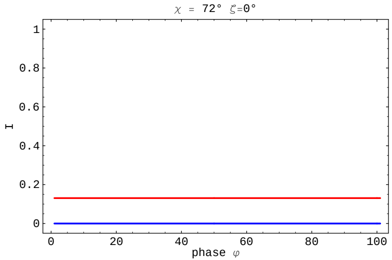

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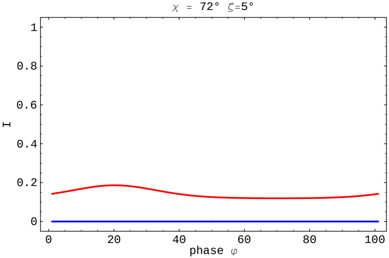

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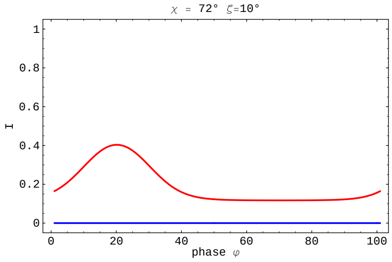

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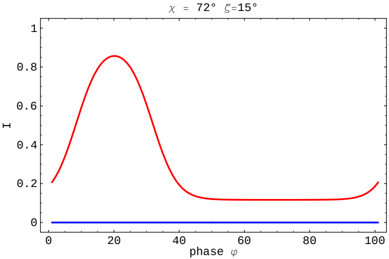

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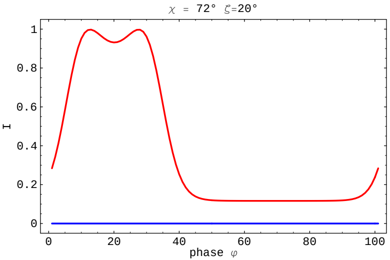

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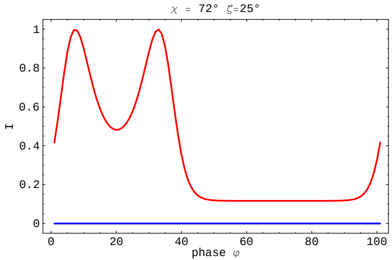

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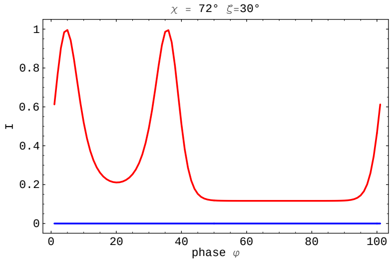

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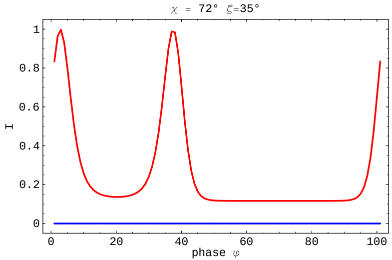

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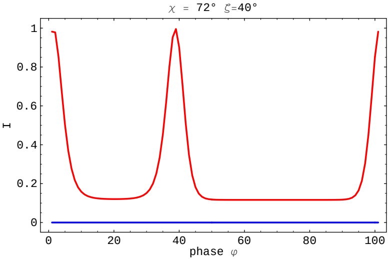

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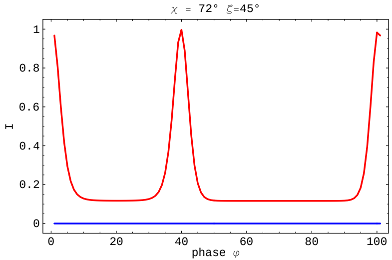

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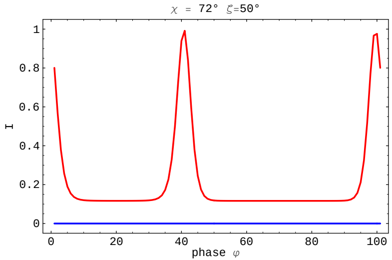

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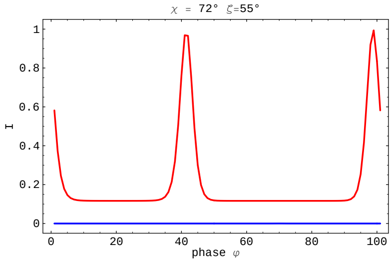

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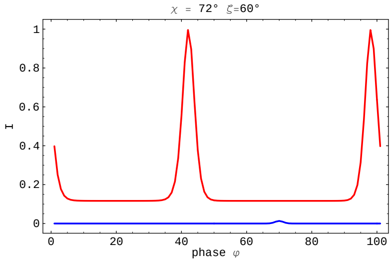

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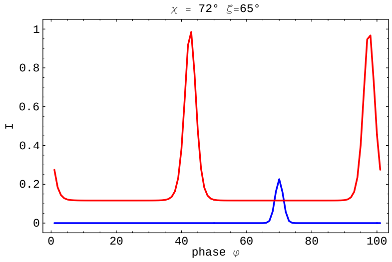

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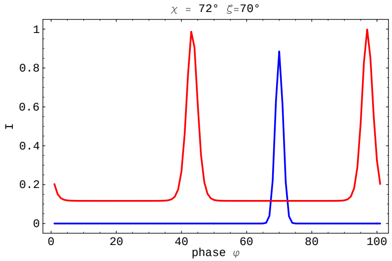

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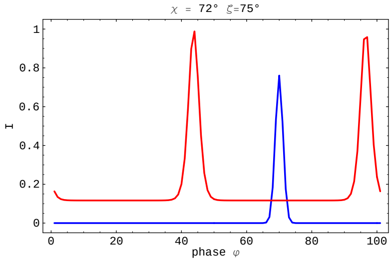

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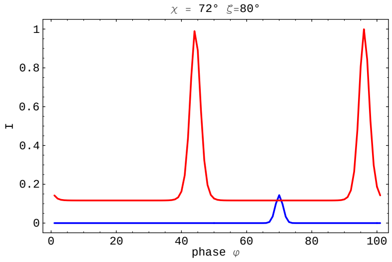

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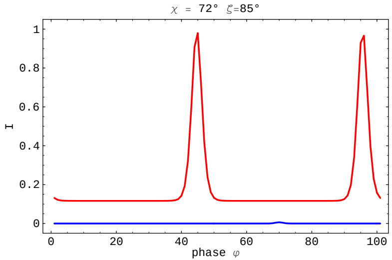

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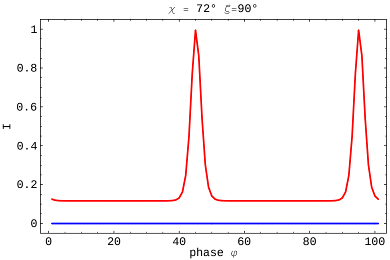

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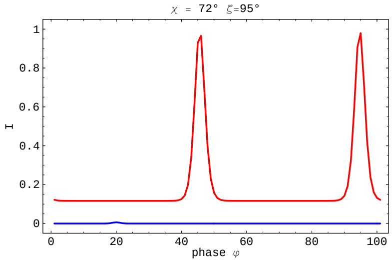

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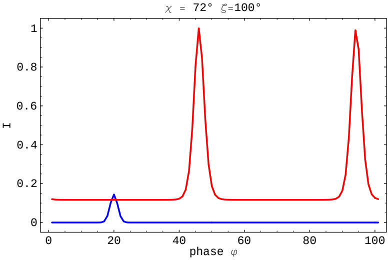

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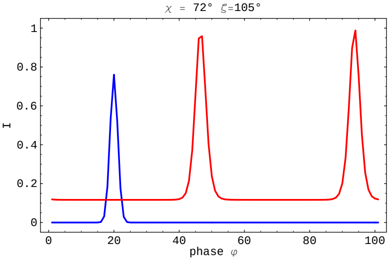

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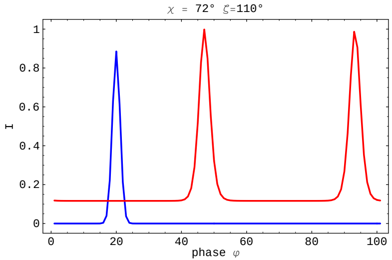

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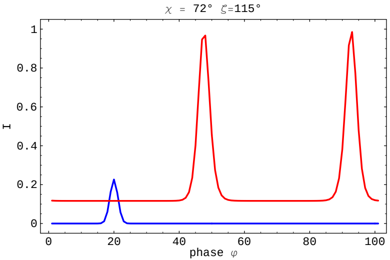

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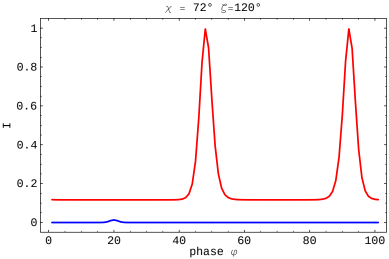

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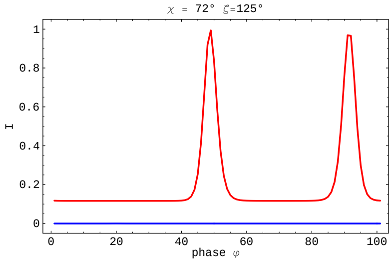

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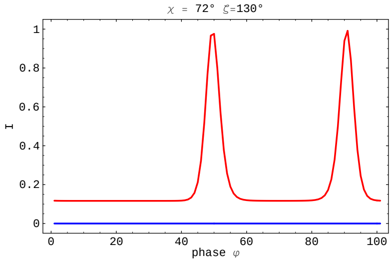

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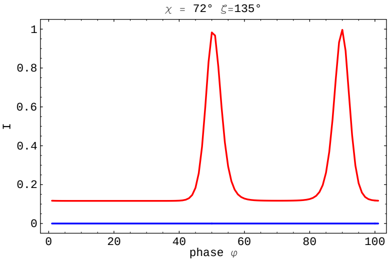

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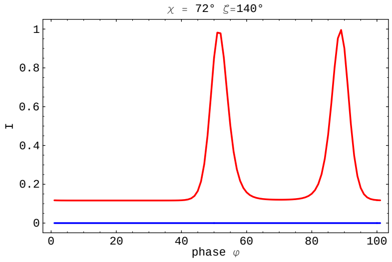

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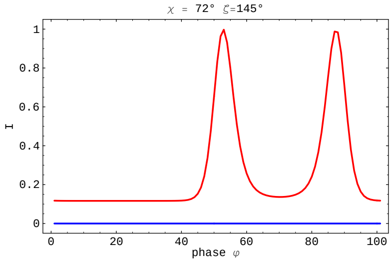

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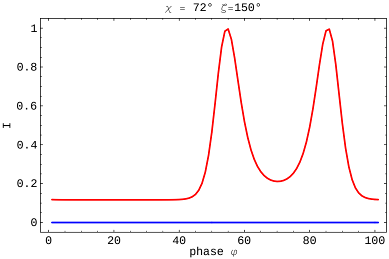

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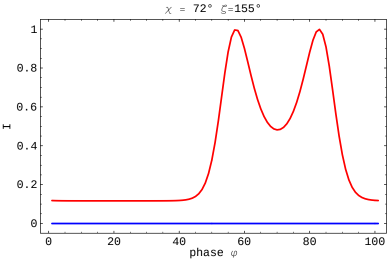

(Pétri, MNRAS, in press)

Main results

- S-shape reflects emission from current sheets
- two spots corresponding to polar cap emission (north & south pole separated by half a period)
- several light-curve combinations possible depending on geometry χ, ζ
  - no pulse !
  - only radio
  - only gamma
  - one radio + one/two gamma-ray pulse(s)
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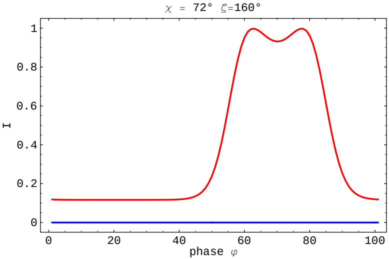

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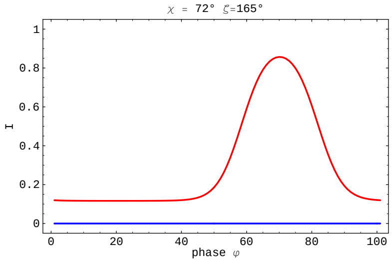

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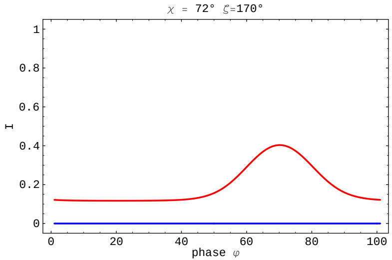

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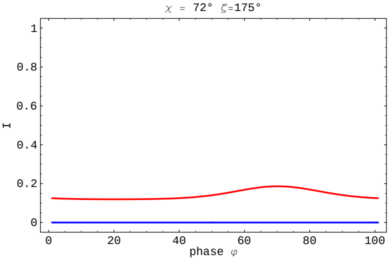

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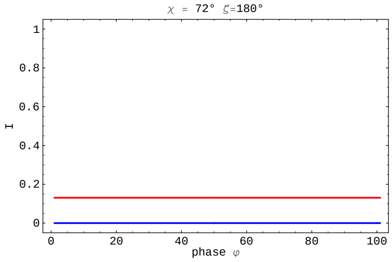


(Pétri, MNRAS, in press)

What changes ?

- location of the termination shock
- strong external target photon field from companion
- variation with orbital phase

The case of PSR B1259-63

Pulsar parameters

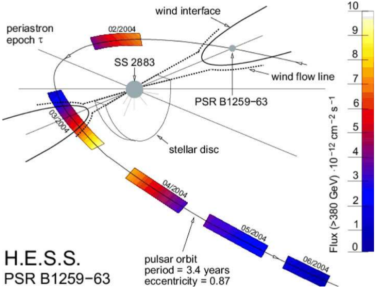
- period $P = 47.7$ ms
- $L_{\rm sd} = 8.3 \times 10^{28}$ W

Feature of the companion Be star known

- $L_* = 3.3 \times 10^{30}$ W
- $\dot{M} = 10^{-8}\ M_\odot/yr$
- $v_{\rm wind} = 1000$ km/s
- separation $d = 9.6 \times 10^{10}$ m to 1.2×10^{12} m

Termination shock
pressure balance implies

$$\frac{R_{\rm TS}}{R_{\rm w}} = \sqrt{\frac{L_{\rm sd}}{\dot{M}\, v_{\rm w}\, c}} \approx 0.7$$



Aharonian et al (2005)

A comparison between radiative cooling times

Three main channels to produce photons

1. synchrotron radiation (polar cap)

$$\tau_{\rm sync} = \frac{3}{4}\,\frac{m\,c}{\sigma_T}\,\frac{1}{\gamma\,U_B} \approx 7.7\,{\rm s}\,\gamma^{-1}\,\left(\frac{B}{1\,{\rm T}}\right)^{-2}$$

2. inverse Compton scattering (wind)

$$\tau_{\rm ic} = \frac{3}{4}\,\frac{m\,c}{\sigma_T}\,\frac{1}{\gamma\,U_\gamma} \approx 1.9\times10^{25}\,{\rm s}\,\gamma^{-1}\,\left(\frac{U_{\rm ph}}{1\,{\rm eV/m^3}}\right)^{-1}$$

3. curvature radiation (outer gap)

$$\tau_{\rm cr} = \frac{e^2}{\sigma_T\,\varepsilon_0\,m\,c^3}\,\frac{R_c^2}{\gamma^3} \approx 1.7\times10^{12}\,{\rm s}\,\gamma^{-3}\,\left(\frac{\rho_c}{1\,{\rm km}}\right)^{2}$$

An estimate of maximum Lorentz factor

- acceleration time in strong electromagnetic field with $E \approx c\,B$

$$\tau_{\rm acc} \approx \frac{\gamma\,m}{q\,B} = \frac{1}{\omega_B}$$

- deduce Lorentz factor by equating

$$\tau_{\rm acc} \approx \tau_{\rm cool}$$

A comparison between radiative cooling times

For a “typical” isolated pulsar

- $R_* = 10$ km
- $P = 100$ ms
- $B_* = 10^8$ T => $B_L \approx 1$ T
- $L_X = 10^{26}$ W
- binary parameters = PSR B1259-63

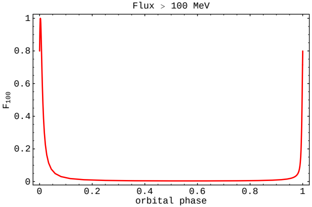
	isolated pulsar			pulsar in binary	
	polar cap	outer gap	wind	outer gap	wind
photon field energy density (J/m^3)					
U_{thermal} (NS surface)	10^8	10	10^{-1}		
U_{comp} (companion)				10^{-1}	10^{-1}
radiative cooling time (s)					
$\gamma^3\,\tau_{\text{cr}}$	10^{16}	10^{19}	10^{21}		
$\gamma\,\tau_{\text{sync}}$	10^{-15}	10	10^3		
$\gamma\,\tau_{\text{ic}}$	10^{-2}	10^5	10^7	10^7	10^7
$\gamma^{-1}\,\tau_{\text{acc}}$	10^{-19}	10^{-11}	10^{-10}		
maximum Lorentz factor γ_{max}					
curvature	10^8	10^7	10^7		
synchrotron	10^2	10^6	a few 10^6		
IC	4×10^8	2×10^8	6×10^8	10^8	10^8

Orbital phase variability

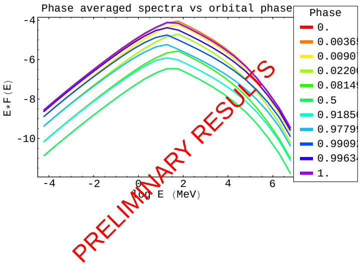
- phase-averaged light-curve depends on orbital phase
- maximum at periastron
- spectral variability with orbital phase
  - spectral slope, transition Thomson/Klein-Nishina regime
  - cut-off and break energy

=> special features for pulsars in binaries

Light curve above 100 MeV



Phase-averaged spectra



Pétri & Dubus, in preparation

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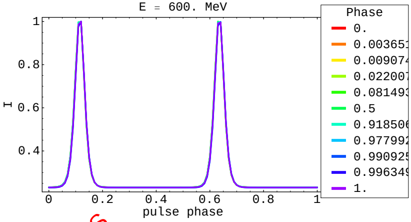
Pulse shape

- no significant dependence on orbital phase
- but strong dependence on energy => relativistic beaming effect, spectral slope (α) dependence ($\mathcal{D}^{3+\alpha}$)
- reflects the properties of the current sheets (thickness, particle distribution)

=> intrinsic characteristics of pulsar wind emission properties

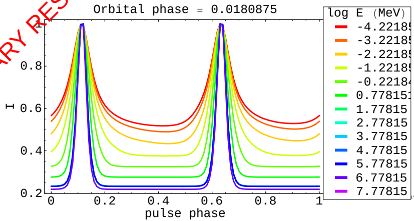
=> independent of isolated/binary nature

Pulse profile changes with orbital phase



Pulse profile changes with energy

PRELIMINARY RESULTS



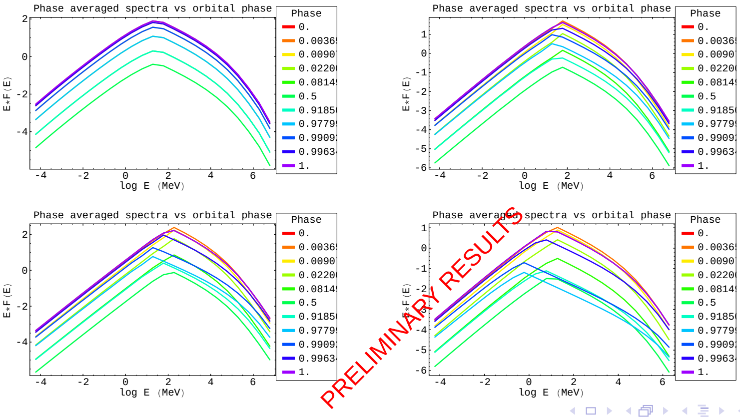
For other gamma-ray binaries : parametric study

- for other binaries, pulsar inside ?
- how to distinguish black hole from neutron star ?

=> maybe striped wind spectral properties with orbital phase

=> parametric study with $i, \Gamma_v, \dots$

Spectral variability with orbital phase for $i = 0, 30, 60, 90^o$



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Conclusions

Pulsed emission

- high-energy pulsed emission emanating from regions well outside the light cylinder, $r \approx \mathrm{few} - 100\, r_{\rm L}$
- phase-resolved optical polarisation properties of the Crab pulsar in agreement with observations
- phase-resolved and spectral variability of MeV-GeV emission explained by inverse Compton scattering of CMB or stellar thermal X-ray photons for several gamma-ray pulsars

Further investigations

- link between asymptotic toroidal magnetic field and magnetosphere $\Rightarrow$ location where most of the high-energy pulsed emission is expected
- refinement of the model to include recent Fermi detections
- possible explanation for gamma-ray binaries ?

Physics

- radiation mechanism
- particle acceleration processes (magnetosphere + wind)

MORE SLIDES

Where we expect to produce emission

Pressure and magnetic field in the stripes Two distinct regions

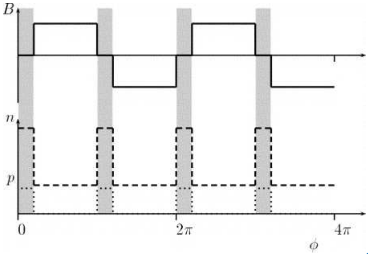
1. current sheets : zero magnetic field $B = 0$, constant pressure p and high particle density number n
   $\Rightarrow$ hot unmagnetized plasma
2. between current sheets : constant magnetic field, zero pressure, low particle density number
   $\Rightarrow$ cold magnetized plasma

Entropy wave

MHD equilibrium implies

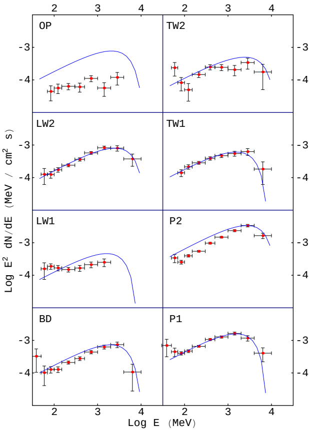
magnetic pressure $\frac{B^2}{2\,\mu_0}$
+
gaseous pressure p
=
constant across the wind
(within an $1/r^2$ factor)

Cross section of an idealized striped wind (Lyubarsky & Kirk, 2001)



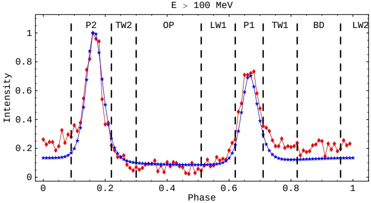
4 Application to isolated pulsars

Phase resolved spectra



(Pétri, A&A 2009)

Light curve above 100 MeV



- observations
- striped wind fit

Parameters

- wind speed $\Gamma_v = 10$
- particle $\gamma \in [10^2, 10^5]$
- power law index $p = 1.6$
- $\chi = 60^o$ and $\zeta = 90^o$

What about gamma-ray binaries ?

Pulsar parameters

- period $P = 47.7$ ms
- $L_{\rm sd} = 8.3 \times 10^{28}$ W

Feature of the companion Be star known

- $L_* = 3.3 \times 10^{30}$ W
- $\dot{M} = 10^{-8} \, M_\odot/yr$
- $v_{\rm wind} = 1000$ km/s
- separation $d = 9.6 \times 10^{10}$ m to 1.2×10^{12} m

Parameters of the model

- $\chi = 85^o$ => almost orthogonal rotator
- $i = 36^o$
- eccentricity $e = 0.87$
- $\Gamma_v = 10$
- particle distribution function $\gamma \in [10^2, 10^6]$
- power law index $p = 2$

Geometrical properties

- the obliquity (χ) of the pulsar (angle between magnetic moment and rotation axis)
- the inclination (ζ) of the line of sight with respect to rotation axis.

Magnetic field configuration

- no radial component, $B_r = 0$ but toroidal and $B_\theta, B_\varphi \propto 1/r$
- the current sheet (discontinuous B_φ) replaced by a transition layer of thickness (Δ_φ) (smooth B_φ polarity reversal)
- accompanied by a significant B_θ component in the current sheet

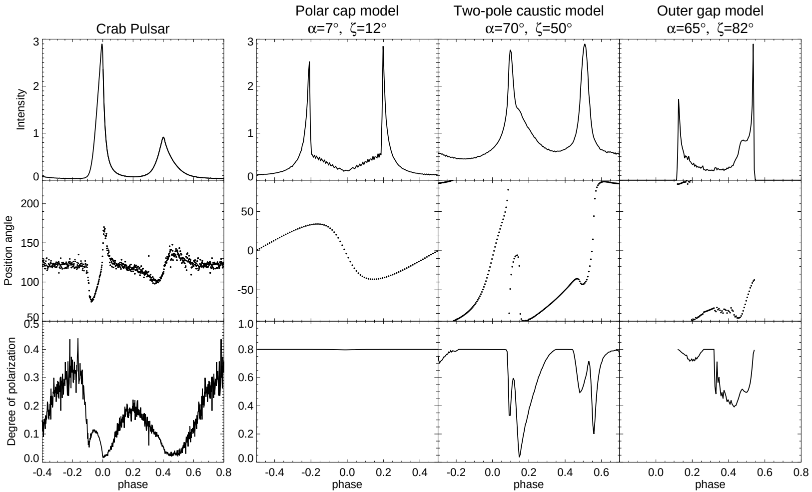
Dynamical properties (emitting particles)

- the Lorentz factor, $\Gamma_{\rm v}$, of the wind
- the power law index, p, of the particle distribution
- the electron/positron number density, $K(\vec{r}, t)$, such that the distribution function (isotropic in momentum space $\vec{\mathcal{P}}$) is

$$N(E, \vec{\mathcal{P}}, \vec{r}, t) = K(\vec{r}, t) \, E^{-p}$$

pressure balance $\Rightarrow$ strong magnetic field associated with low density and conversely.

Polar/outer gap and two-pole caustic model



(Dyks et al. 2004)

“Standard” cartoons : corotating magnetosphere filled with plasma

1. the polar cap (Sturrock 1971, Ruderman & Sutherland 1975)
   - particle acceleration and radiation close to the neutron star surface (at the magnetic poles).
2. the outer gap (Cheng et al. 1986)
   - particle acceleration and radiation in the vicinity but inside the light cylinder.
3. the two-pole caustic (Dyks & Rudak 2003)
   - particle acceleration and radiation from the neutron star surface up to the light cylinder.

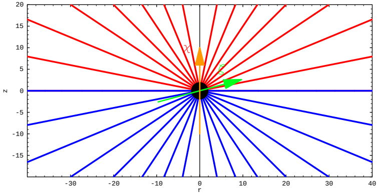
Some alternative models

1. the electrosphere (Krause-Polstorff & Michel 1985, Pétri et al. 2002a)
   - the magnetosphere is almost completely empty !
   electrosphere $\equiv$ regions of the magnetosphere filled with a non-neutral plasma
   $\Rightarrow$ physics of pulsar electrosphere much more complicated and interesting than the previous cartoons

   diocotron and magnetron instabilities
   (Pétri et al. 2002b, 2003, Pétri, 2007a,b, 2008)
2. the striped wind (Coroniti 1990, Michel 1994)
   radiation emanating from outside the light cylinder.

The split monopole solution

Aligned rotator (Michel 1973)



Definition

Two half monopoles with equal and opposite magnetic moment, each located in one half-space (depicted in red and blue).

Properties

- exact analytical solution exists
- asymptotic structure as an archimedean spiral, strength of azimuthal magnetic field B_φ decreasing as $1/r$
- magnetic polarity change in the equatorial plane
  $\Rightarrow$ formation of a current sheet

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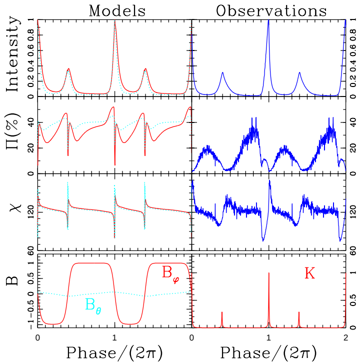
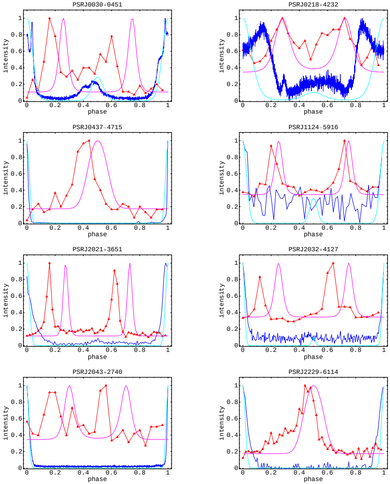
Polarisation properties of the pulsed emission

Pulsed emission emanating from the wind



Pétri & Kirk (2005)
Observations (Kanbach et al. 2003)

Pulsed emission emanating from the wind

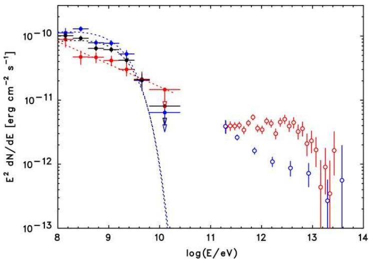


Pétri, MNRAS in press

Gamma-ray binaries : black hole or neutron star ?

- spectral variability and pulse unique to the striped wind model
- BUT no pulse does not exclude a neutron star
- geometry dependent
- polarization in X-ray or soft gamma-ray ?
- hints on magnetic field geometry
- different populations dominant at inf/sup conjunction ?
  - unshocked wind : cold magnetized/hot unmagnetized
  - shocked wind

Spectra of LS5039



Abdo et al, ApJL, 2009