Polarisation of high-energy emission in a pulsar striped wind

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Outline

1. The models
2. The striped wind
3. Application to the Crab pulsar
4. Conclusions & Perspectives

The existing models

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

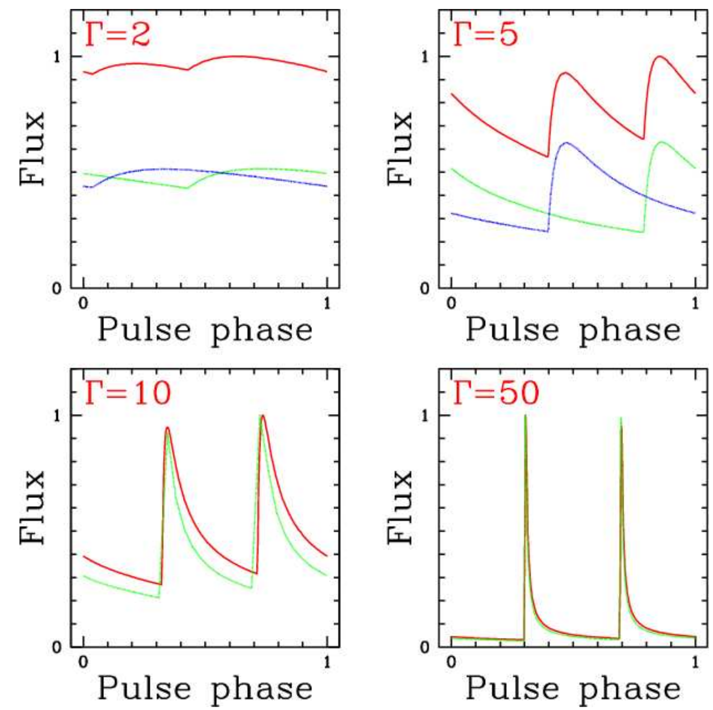
4. the electrospheric structure (Krause-Polstorff & Michel 1985, Pétri et al. 2002) ;
   the magnetosphere is almost empty !
5. the striped wind (Coroniti 1990, Michel 1994).
   radiation well outside the light cylinder.

Aim of this work

1. to compute the polarisation properties of the synchrotron emission in the relativistic striped wind.

   Relativistic beaming effect $\Rightarrow$ pulsed emission

2. to make a quantitative comparison with the recent optical data from the Crab pulsar (Kanbach et al. 2003).

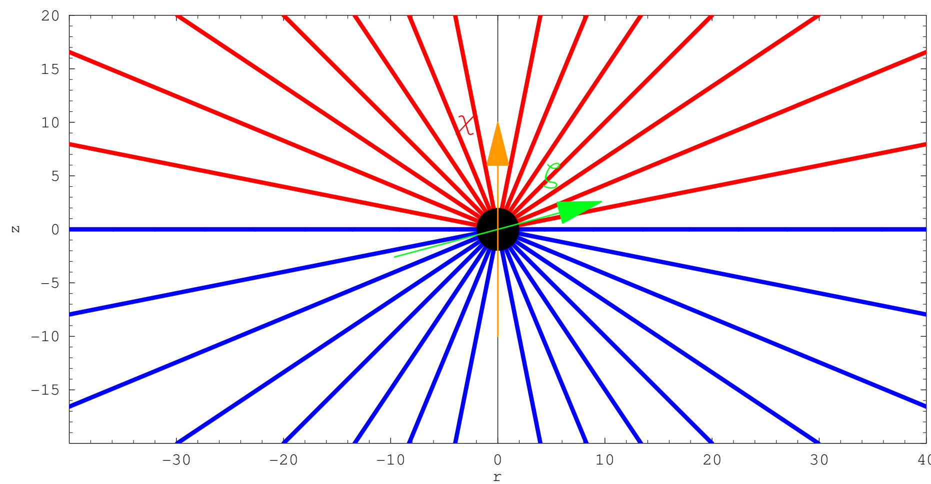


(Kirk et al. 2002)

This will complete the work of Dyks et al. (2004) who studied the synchrotron polarisation for the outer/polar gap and two-pole caustic models.

The split monopole solution

Aligned rotator (Michel 1973).



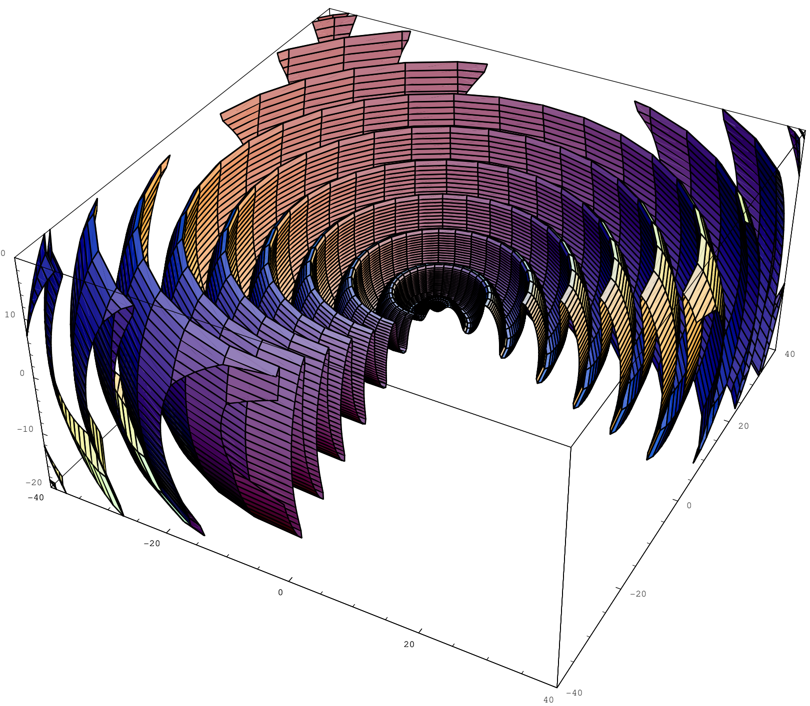
2 half monopoles with equal and opposite magnetic moment, each located in one half-space (depicted in red and blue).

Properties :

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

The striped wind

Asymptotic MHD wind solution (Bogovalov 1999).



- 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 polarity reversal.

Parameters of the model (1)

Geometrical properties :

- the obliquity (χ) of the pulsar (angle between magnetic moment and rotation axis) ;
- the inclination (ζ) of the line of sight ;

Magnetic field configuration :

- no radial component, $B_r = 0$;
- azimuthal and colatitudinal components follow the split monopole decay in radius, $B_\theta, B_\varphi \propto 1/r$;
- the current sheet (discontinuous B_φ) replaced by a transition layer of thickness (Δ_φ) (smooth polarity reversal) ;
- the width of significant B_θ component (Δ_θ) :
- the maximum relative amplitude ($b_{1,2}$) of the B_θ compared to B_φ defined in each pulse.

Parameters of the model (2)

Dynamical properties (emitting particles) :

- the Lorentz factor (Γ) 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 $\vec{p}$) is :

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

and chosen to mimic the total pressure balance between magnetic and gaseous component

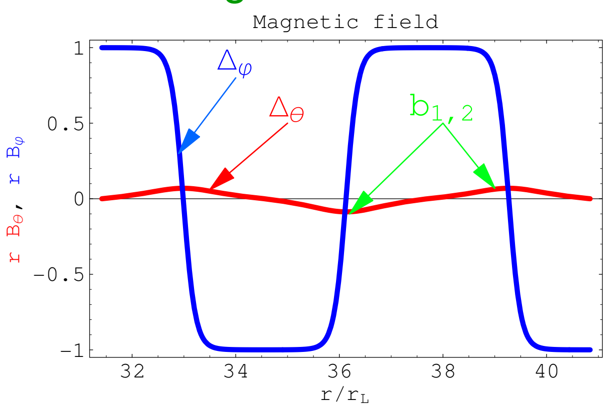
$$\frac{B^2}{2\,\mu_0} + P_g = \frac{cste}{r^2}$$

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

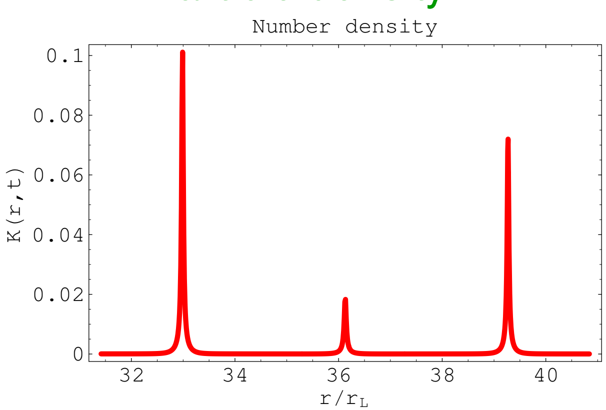
An example

In the equatorial plane $(\theta = \pi/2, \varphi = 0, t = 0)$

Magnetic field



Particle density



Magnetic field :

- magnetic field B_φ polarity reversal in the current sheet ;
- accompanied by a significant B_θ component ;

Particle density :

- $e^\pm$ density non negligible in these transition layers ;
- asymmetry in the peak density to account for the pulse maximum intensity discrepancy.

Polarisation parameters

With help on the aforementioned Stokes parameters (I, Q, U), we plot :

- the normalized intensity :

$$I_{\rm norm} = \frac{I}{I_{\rm max}}$$

- the polarisation degree :

$$\Pi = \frac{\sqrt{Q^2 + U^2}}{I}$$

- the polarisation angle, defined as the position angle between the total electric field vector received by an observer and the projection of the pulsar's rotation axis on the plane of the sky is:

$$\chi = \frac{1}{2} \arctan\left(\frac{U}{Q}\right)$$

Application to the Crab pulsar

The geometrical parameters
(Ng & Romani 2004) :

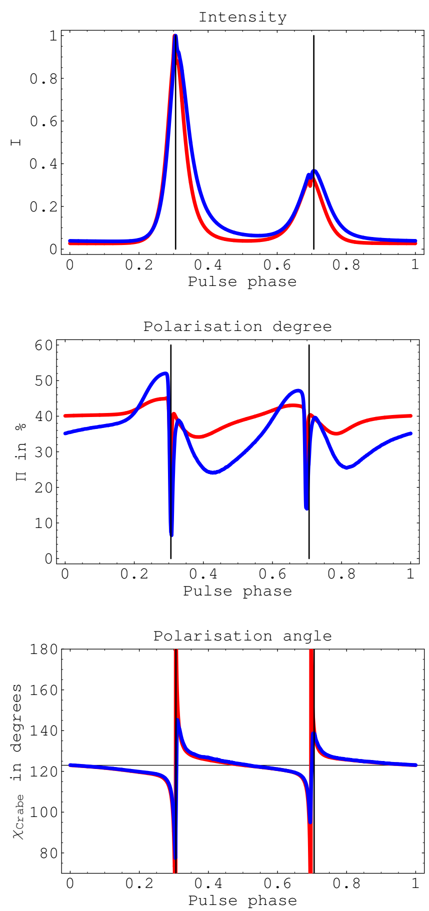
- the obliquity $\chi = 60^o$;
- the line of sight inclination angle $\zeta = 60^o$;
- the angle of the rotation axis of the pulsar on the plane of the sky $\Psi = 123^o$.

For the emitting particles :

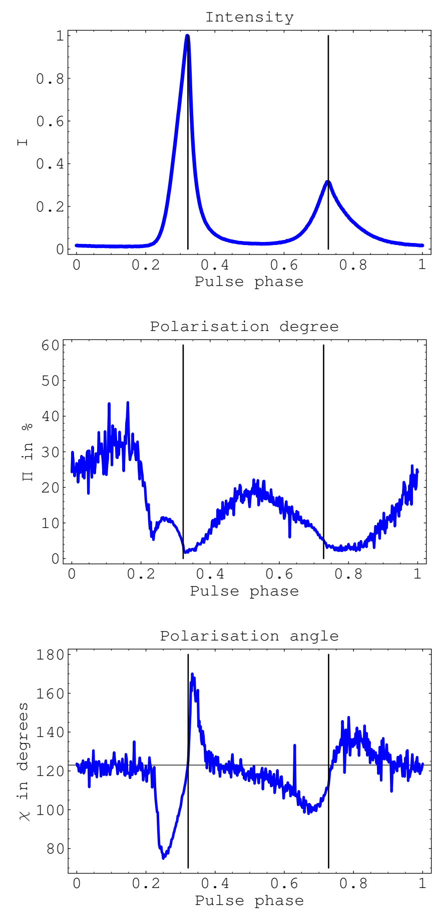
- the power law index $p = 2$.

Polarisation properties of the pulsed emission

Models with $\Gamma = 20, 50$



Observations (Kanbach et al. 2003)



(Pétri & Kirk, ApJL 2005)

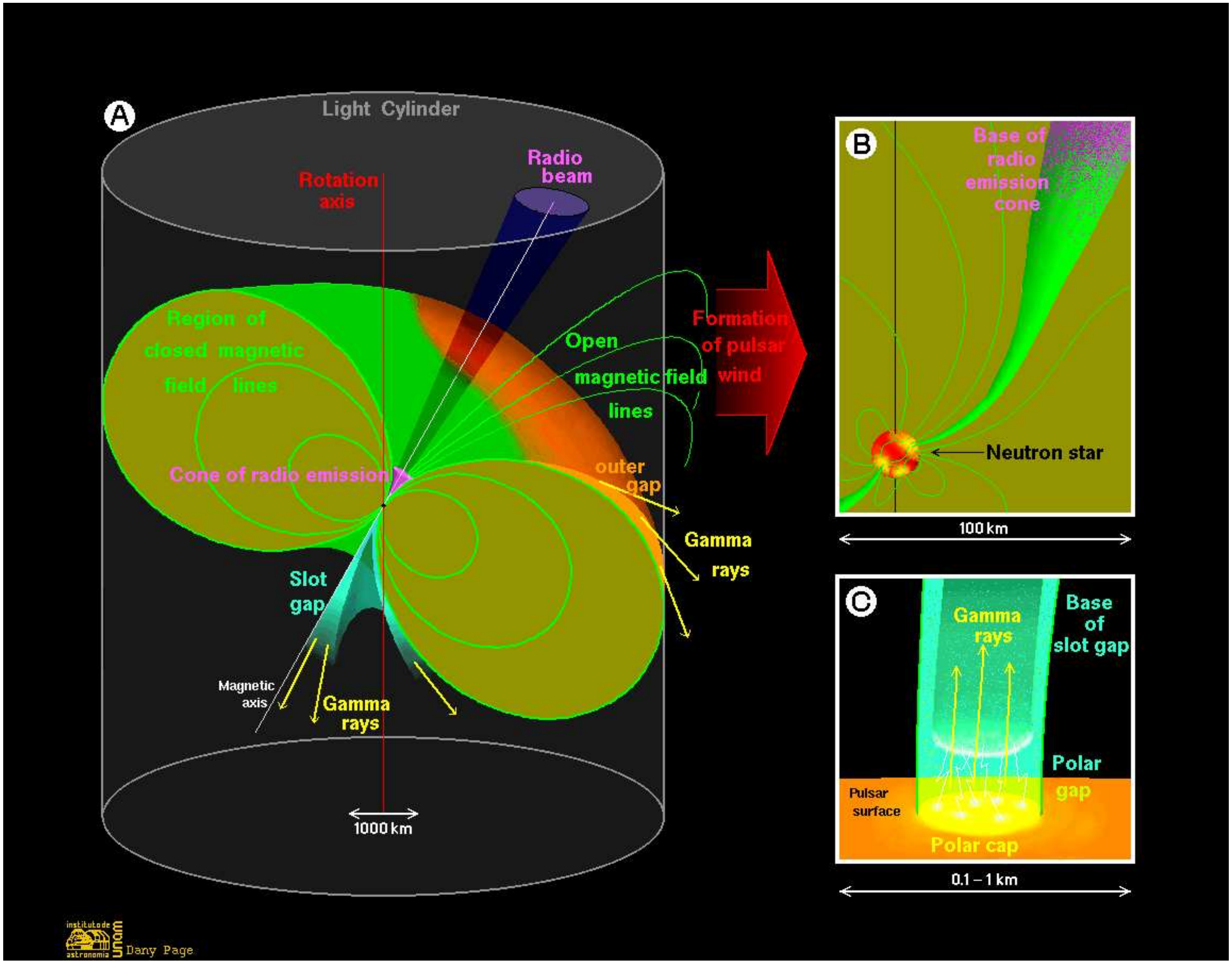
Conclusions

- pulsed high-energy emission of pulsars arises from regions well outside the light cylinder ;
- electric vector of the off-pulse emission is aligned with the projection of the pulsar's rotation axis on the plane of the sky :
- computations are in agreement with recent observations of the Crab pulsar ;
- the striped wind scenario naturally incorporates features of the phase-dependent properties of the polarisation angle, degree of polarisation and intensity.

Perspectives

- the manner in which magnetic energy is released into particles in the current sheet remains poorly understood ;
- the link between the asymptotic magnetic field structure and the pulsar magnetosphere is obscure.

The “standard” model



Stokes parameters (1)

Stokes parameters $(I, Q, U, V = 0)$ as measured by an observer at time $t_{\rm obs}$:

$$\left\{ \begin{array}{c} I_\omega \\ Q_\omega \\ U_\omega \end{array} \right\} (t_{\rm obs}) = \int_{r_0}^{+\infty} \int_0^{\pi} \int_0^{2\,\pi} s_0(r, \theta, \varphi, t_{\rm ret}) \left\{ \begin{array}{c} \frac{p+7/3}{p+1} \\ \cos(2\,\tilde{\chi}) \\ \sin(2\,\tilde{\chi}) \end{array} \right\} r^2 \, \sin\theta \, dr \, d\theta \, d\varphi$$

- emission starts for $r \geq r_0$;
- $t_{\rm ret} = t_{\rm obs} + \vec{n} \cdot \vec{r}/c$ is the retarded time :
- $\vec{n}$ is a unit vector along the line of sight from the pulsar to the observer ;
- ω is the angular frequency of the emitted radiation ;
- $\tilde{\chi}$ is the local polarisation angle at a given point (r, θ, φ, t).

aberration of light causing a rotation in the polarisation angle (relativistic kinematics effect, included in the definition of $\tilde{\chi}$).

Stokes parameters (2)

The function s_0 is defined by the synchrotron emissivity:

$$s_0(r, \theta, \varphi, t) \quad = \quad \kappa\, \omega^{-\frac{p-1}{2}}\, K(\vec{r}, t)\, \mathcal{D}^{\frac{p+3}{2}} \left(\frac{B}{\Gamma} \sqrt{1 - (\mathcal{D}\, \vec{n} \cdot \vec{b})^2} \right)^{\frac{p+1}{2}}$$

- κ is a constant factor that depends only on the nature of the radiating particles (charge q and mass m) and the power law index p of their distribution;
- $\mathcal{D}$ the Doppler boosting factor:

$$\mathcal{D} = \frac{1}{\Gamma\,(1 - \vec{\beta} \cdot \vec{n})}$$

- $\vec{b}$ is a unit vector along the magnetic field line ;

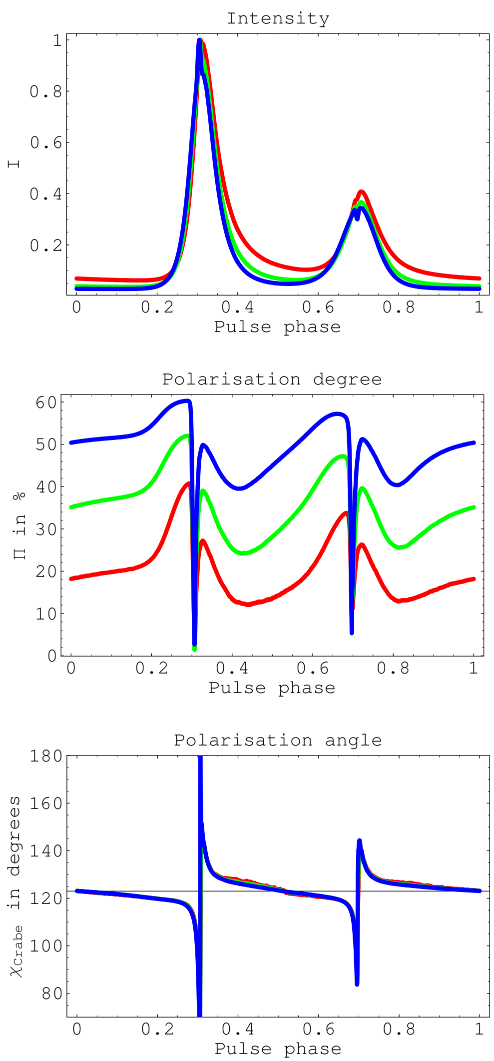
κ function

$$\kappa = \frac{\sqrt{3}}{2\,\pi}\,\frac{1}{4}\,\Gamma_{\mathrm{Eu}}\left(\frac{3\,p+7}{12}\right)\,\Gamma_{\mathrm{Eu}}\left(\frac{3\,p-1}{12}\right)\,\frac{|q|^3}{4\,\pi\,\varepsilon_0\,m\,c}\,\left(\frac{3\,|q|}{m^3\,c^4}\right)^{\frac{p-1}{2}}$$

with Γ_{Eu} the Euler gamma function

Influence of p

Model with $p = 1, 2, 3$



- light curves and polarisation angle unchanged by varying p ;
- average polarisation degree correlated with p ;
- indeed, in the most favorable case (straight magnetic field lines), the maximum degree of polarisation is :

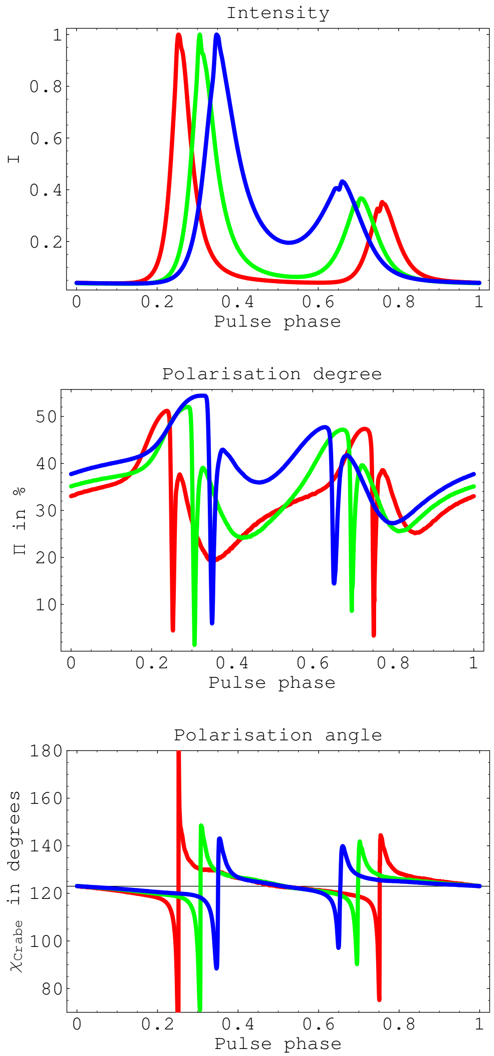
$$\Pi_{\mathrm{max}} = \frac{p+1}{p+7/3}$$

For instance,

$$\Pi_{\mathrm{max}}(p = \left\{ \begin{array}{c} 1 \\ 2 \\ 3 \end{array} \right\}) = \left\{ \begin{array}{c} 60\% \\ 69\% \\ 75\% \end{array} \right\}$$

Influence of ζ

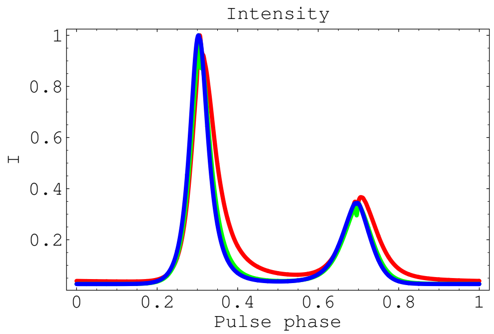
Model with $\xi = \pi/2, \pi/3, \pi/4$

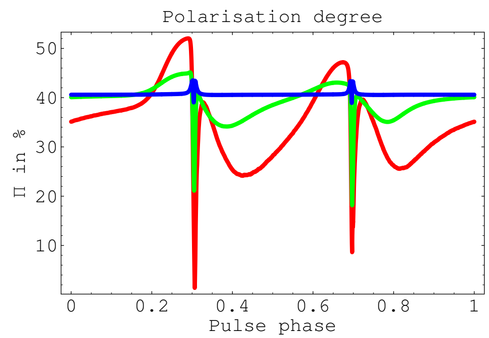


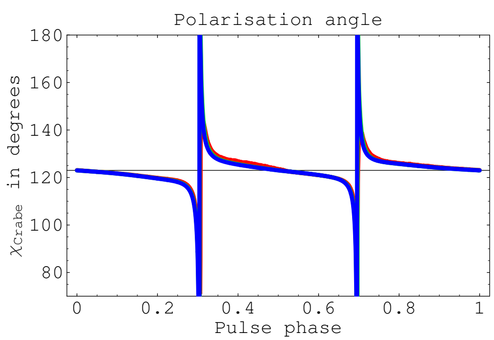
- peak separation and correlated quantities (degree of polarisation and angle sweep) depending on the inclination of the line of sight :
- but relative peak intensity preserved ;
- degree of polarisation weakly disturbed ;
- sweep angle reaches 180^o in the symmetric case $\zeta = \pi/2$.

Influence of Γ

Model with $\Gamma = 20, 50, 500$



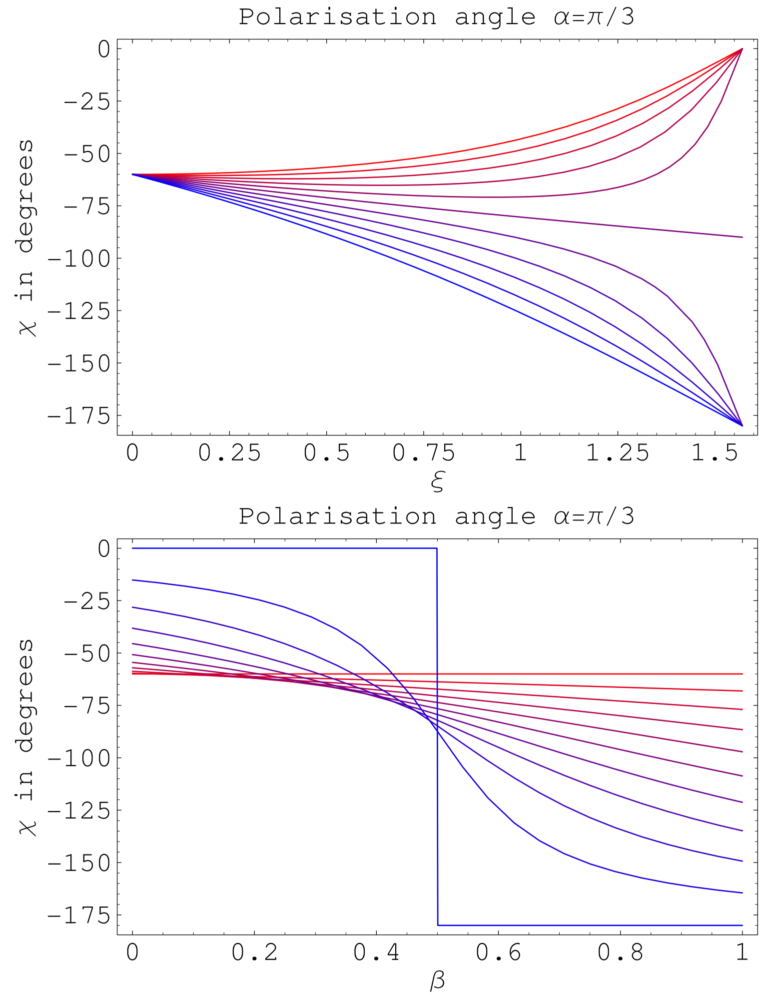




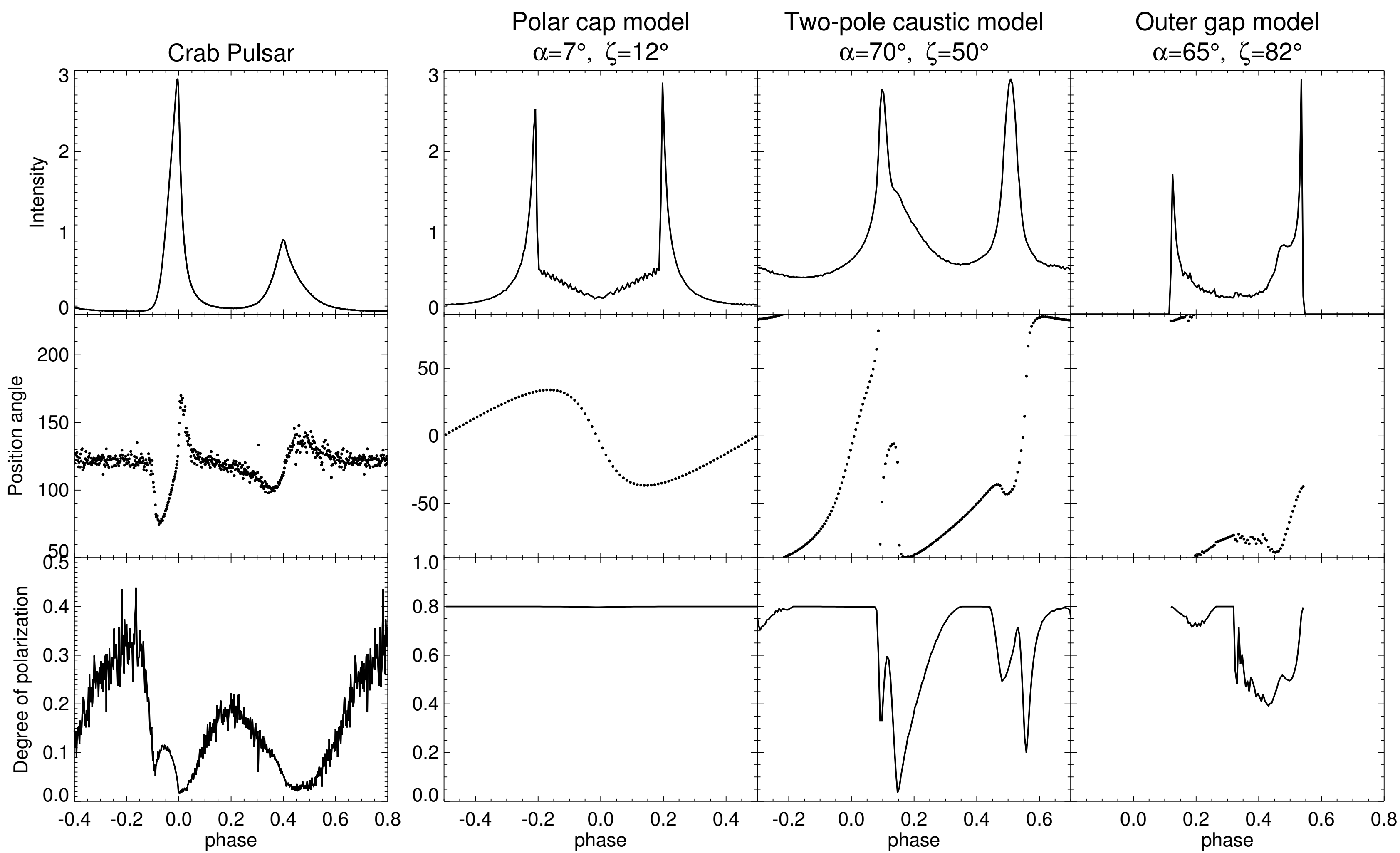
In the ultrarelativistic regime $\Gamma \gg 1$:

- the polarisation degree reaches a constant limit for high Lorentz factors ;
- sweep angle of 180^o ;

Aberration of light



Polar/outer gap and two-pole caustic model



(Dyks et al. 2004)