Pulsar winds and magnetospheres:
emission, acceleration and magnetic reconnection

Jérôme Pétri

Observatoire Astronomique de Strasbourg
Université de Strasbourg

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Outline

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What is a pulsar ?

Pulsar magnetosphere : general picture

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1. neutron star
   compact object ⇒ strong gravity effects

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   $\Rightarrow$ plasmas, QED effects (pair creation)

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   $\Rightarrow$ huge electric fields

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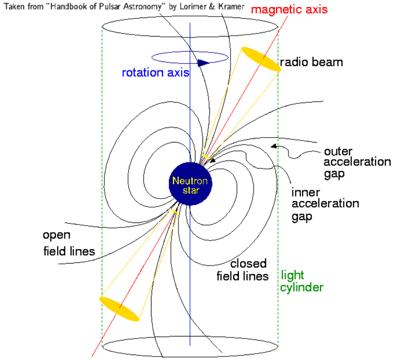
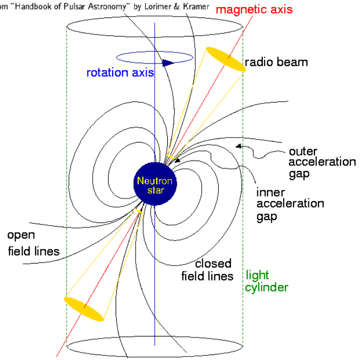


Credit : A.K. Harding



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   compact object ⇒ strong gravity effects
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   ⇒ plasmas, QED effects (pair creation)
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Some useful definitions

- obliquity χ : angle between magnetic $\vec{\mu}$ and rotation $\vec{\Omega}$ axis
- aligned/perpendicular/oblique rotator : $\chi = 0/90^o/$any value
- light cylinder radius : surface on which a particle corotating with the neutron star reaches the speed of light c : $r_L = c/\Omega_*$
  ⇒ transition from quasi-static to wave zone

Some questions related to pulsars/neutron stars

From the interior to the nebula

1. their internal structure : composition & equation of state at very high densities (higher than those of a nucleus)
   $\Rightarrow$ consequences for their global properties : M, R, I, B, Ω.
2. their magnetosphere : what are the composition/distribution functions $f(\vec{r}, \vec{p}, t)$ of the particles (electrons, positrons, maybe protons and/or ions) ?
3. the emission mechanism : a high and very high energy (GeV, TeV) activity ill understood.
4. acceleration and structure of the stellar wind : analogy with the solar wind ?
5. dissipation of the magnetic field into kinetic energy for the particles : magnetic reconnection at work ?
6. pulsars : why pulsed emission ?

Neutron stars main classes

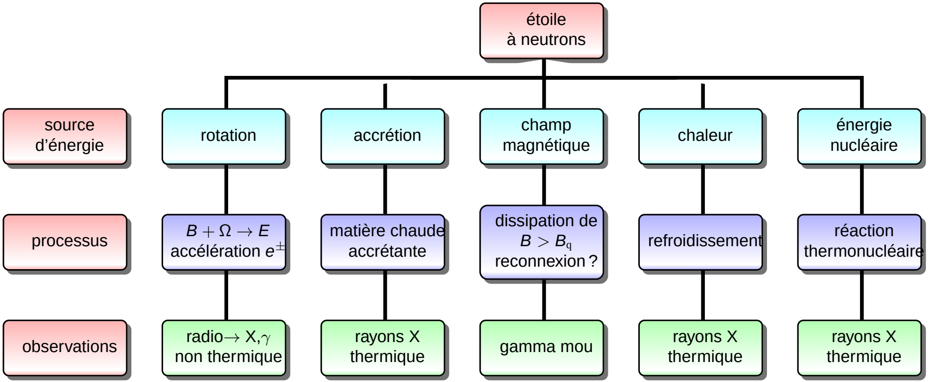


FIGURE: Les différentes classes de pulsars dont la distinction se fait par la source d'énergie à l'origine de l'activité de l'étoile à neutrons.

From observations

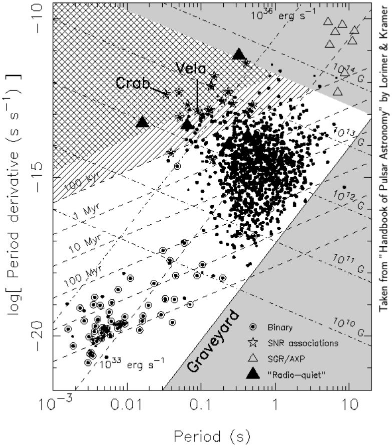
- period $P \in [1\,ms, 1\,s]$.
- period derivative $\dot{P} \in [10^{-18}, 10^{-15}]$.
- spin-down losses well constrained

$$L_{sp} = 4\,\pi^2\,I\,\dot{P}\,P^{-3} \approx 10^{24-31}\;W$$

very different from black holes or accreting neutron stars.

- inferred magnetic field estimate by dipole radiation

$$B = 3.2 \times 10^{15}\,\sqrt{P\,\dot{P}} = 10^{5-8}\;T$$



Credit : Lorimer & Kramer

Electromagnetic and gravitational field characteristics

- electric field induced at the stellar crust

$$E = \Omega\, B\, R = 10^{13}\ \mathrm{V/m}$$

$\Rightarrow$ instantaneous acceleration at ultra-relativistic speeds, Lorentz factor $\gamma \gg 1$ ($\tau_{\mathrm{acc}} < 10^{-20}$ s)

- negligible gravitational force because for protons

$$\frac{F_{\mathrm{grav}}}{F_{\mathrm{em}}} \approx \frac{G\, M\, m_p / R^2}{e\, \Omega\, B\, R} \approx 10^{-12} \ll 1 \qquad (1)$$

- even smaller for electrons/positrons (m_e/m_p).

$\Rightarrow$ dynamic of the magnetosphere dominated by the electromagnetic field.

Neutron star average characteristics

- mass $M \approx 1.4\, M_\odot$.
- radius $R \approx 10$ km.
- central density $\rho_c \approx 10^{17}\ \mathrm{kg/m^3}$.

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Difficult to summarize all observations and behaviors faithfully.

Observations

- individual observation of pulses impossible (except for rare cases).
- very strong variability of individual pulses.
- but mean (averaged/integrated) profile extremely stable.

⇒ average over several hundredth of periods.

⇒ signature unique to each pulsar (its fingerprint).

In a pictural way

- mean profile = climate
- one pulse = weather

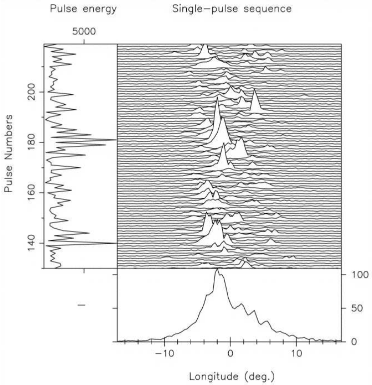


FIGURE: Mean profile and individual pulses of PSR B0943+10 (Deshpande ApJ, 1999)

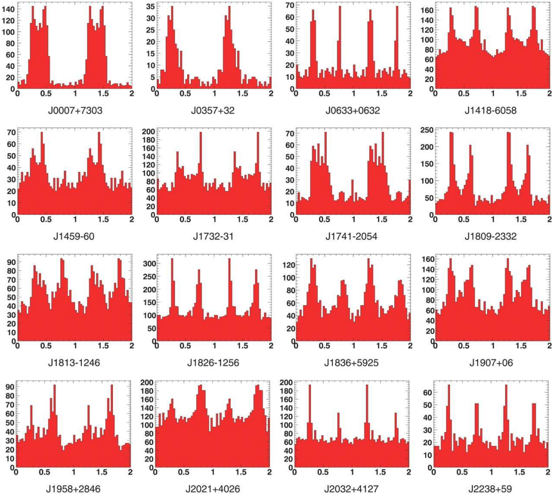
- more than 125(145 ?) gamma-ray pulsars known so far
  - (a) young and energetic, visible in the whole electromagnetic spectrum (Crab).
  - (b) young and radio-quiet (Geminga).
  - (c) old (millisecond).
- light-curves are usually double peaked (75%), separated by 0.3 in phase.
- flux above 100 MeV is about $dN/dE \approx 10^{-8}\ \mathrm{ph/cm^2/s}$.
- mean spectra (integrated over the period) described by a power-law with exponential cut-off

$$\frac{dN}{dE} \propto E^{-\Gamma} e^{-E/E_c} \tag{2}$$

  index $\Gamma \approx 1 - 2$ whereas cut-off energy $E_{cut} \approx 1 - 5$ GeV.
- spin-down luminosity spreads over many decades, $L_{rot} \approx 10^{26} - 10^{31}$ W.
- gamma-ray luminosity L_γ between 0.1% and almost 100% of L_{rot}
  $\Rightarrow$ all the reservoir of energy converted into photons !
- cut-off E_{cut} gives some hints about the sites of production of radiation.

(Abdo et al, ApJS, 2009, update by The Fermi-LAT collaboration, arXiv :1305.4385)

Gamma-ray pulsars : examples



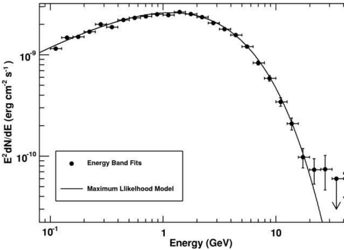
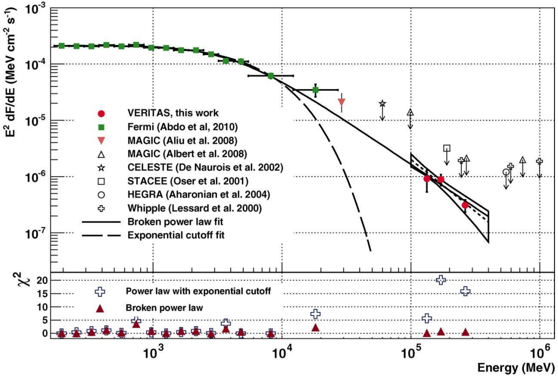


FIGURE: Light-curves of some gamma-ray pulsars, left, (Abdo et al, Science 2009) and Vela mean spectrum, right (Abdo et al, 2010).

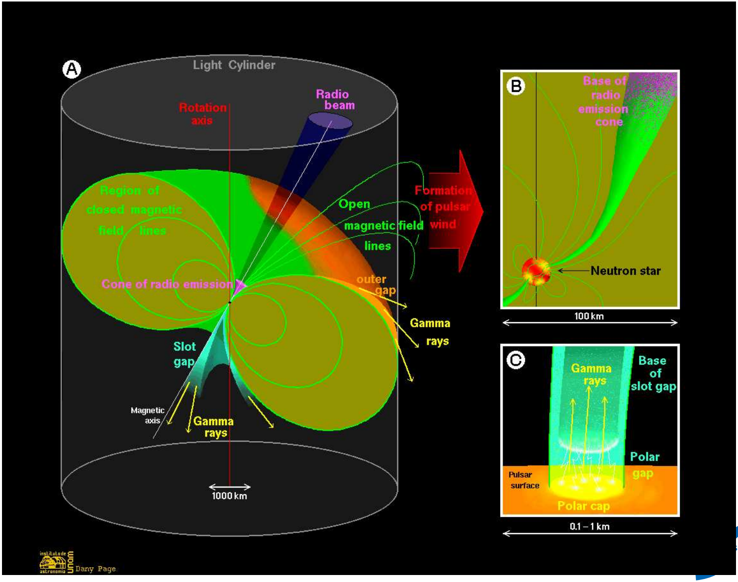
- detection of pulsed emission from the Crab at 200-400 GeV.
- compatible with the spectrum in the Fermi band.
- spectrum as a broken power low rather exponential cut-off.

⇒ kills all existing magnetospheric emission models !



(McCann et al, ICRC 2011)

The “standard model” of a pulsar



Basic underlying assumption : force-free magnetosphere

$$\rho_e \vec{E} + \vec{j} \wedge \vec{B} = \vec{0}$$

magnetic energy density $\frac{B^2}{2\,\mu_0} \gg$ any other energy densities

- particle inertia neglected : zero mass limit.
- no dissipation : ideal MHD

$$\vec{E} + \vec{v} \wedge \vec{B} = \vec{0}.$$

- no pressure : cold plasma.

Two interpretations

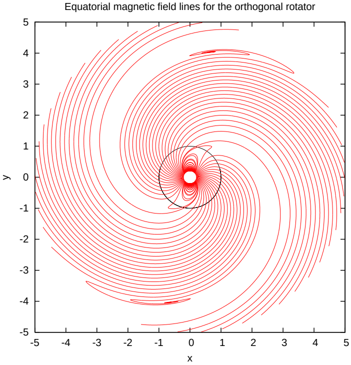
- charge-separated plasma $\Rightarrow$ low particle density.
- MHD model $\Rightarrow$ quasi-neutral plasma, high particle density.

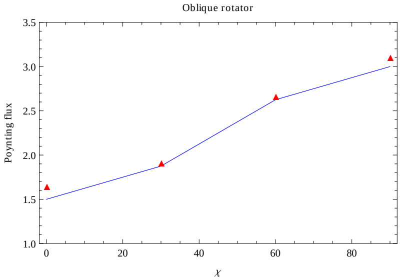
Who is right ? Pulsar Wind Nebula (PWN) will give some clues.

A problem

$\Rightarrow$ the total charge of the system is not conserved a priori.

$\Rightarrow$ total electric current does not vanish !





$$L_{\rm sp}^{ffe} \approx \frac{3}{2} \, L_{\rm dip}^{\perp} \, (1 + \sin^2 \chi) \quad (3a)$$

$\Rightarrow$ more realistic formula than the magneto-dipole in vacuum

$$L_{\rm sp}^{vac} \approx L_{\rm dip}^{\perp} \, \sin^2 \chi \quad (4a)$$

$\Rightarrow$ $B_\perp$ AND $B_\|$ constrained (not the case for vacuum).

(Pétri, MNRAS, 2012a)

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Space-time curvature and frame dragging modify the structure of the electromagnetic field close to the neutron star surface

- amplification of the intensity of the electric field in the neighborhood of the stellar surface because of the gravitational field (Schwarzschild metric, static diagonal part).
- appearance of a longitudinal electric field (along $\vec{B}$) by Lense-Thirring effect (Kerr black hole, off diagonal elements of the metric).

(Muslimov & Tsygan, 1992)

Consequences on the magnetosphere

Quantitative modifications of

- the geometry of the polar caps, opening angle.
- the shape of the radio pulses.
- the modulation of the light-curves in X-rays for accreting pulsars.
- the spin-down luminosity, increase by a factor 5-6 (Pétri, MNRAS, in press).

Emission processes : incoherent radiation

- curvature radiation : a charged particle accelerated along a curved magnetic path will radiate (obliged to follow magnetic field lines).
- cyclotron emission : a charged particle evolving non-relativistically in a magnetic field (special case of curvature radiation for a circular trajectory).
- synchrotron emission : when the same charged particle reaches relativistic speeds, foward beaming of radiation $\Rightarrow$ transition from cyclotron to synchrotron.
- inverse Compton scattering(IC) : relativistic leptons scattering photons
  - thermal photons from the (X-rays).
  - photons from the surrounding nebula.
  - photons from a companion (if binary).
  - cosmic microwave background.
- synchroton-self Compton emission(SSC) : IC of the synchrotron photons produced by the leptons themselves.

BUT does not explain the radio which is peculiar because it is coherent
$\Rightarrow$ need for a coherent emission mechanism.

Emission processes : coherent radiation

Some candidates are

- antenna : beam of particles with dispersion in velocity negligible and radiate in phase
  curvature radiation by a coherent beam for example
  $\Rightarrow$ difficult to set up because beam must be thin and coherence destroyed quickly.
- plasma instability : weak dispersion in velocity, particles in phase with increasing perturbation, two-stream for instance.
- maser effect with negative absorption : population inversion in the Landau levels.

No agreement yet on the processes really at work in the magnetosphere.

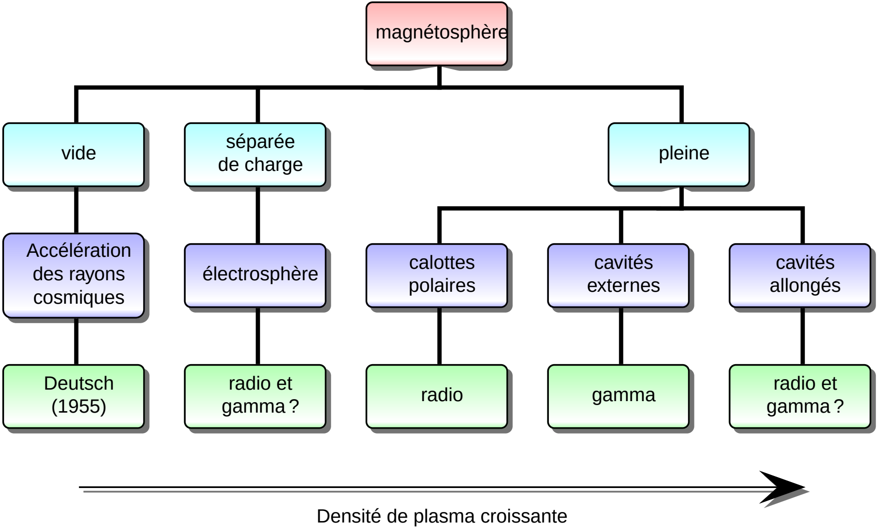

FIGURE: Vue synthétique des modèles de magnétosphère de pulsar. Les modèles peu denses sont situés à gauche tandis que les magnétosphères pleines et denses se situent à droite.

- the pulsar and its magnetosphere, source of *relativistic* $e^{\pm}$ *pairs*.

FIGURE: Link between the pulsar and its surrounding nebula.

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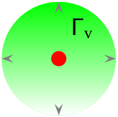
- the cold ultra-relativistic wind streaming to the nebula.



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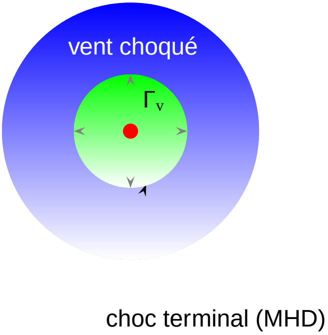
- the pulsar and its magnetosphere, source of *relativistic* $e^{\pm}$ *pairs*.
- the cold ultra-relativistic wind streaming to the nebula.
- the shocked wind composed of particles heated after crossing the *MHD shock* $\Rightarrow$ *main source of radiation* observed in radio, optics, X-rays and gamma-rays.



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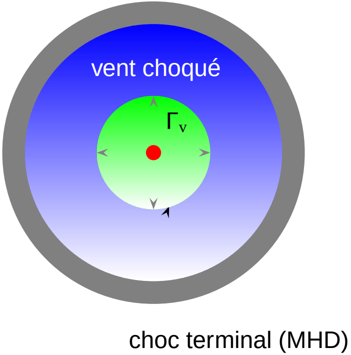
- the supernova remnant.



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Supernova remnant and nebula

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- the shocked wind composed of particles heated after crossing the *MHD shock* $\Rightarrow$ *main source of radiation* observed in radio, optics, X-rays and gamma-rays.
- the supernova remnant.
- the interstellar medium.

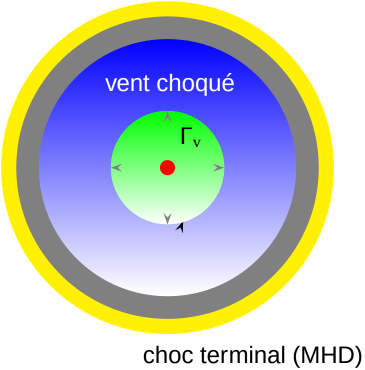
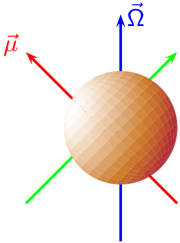


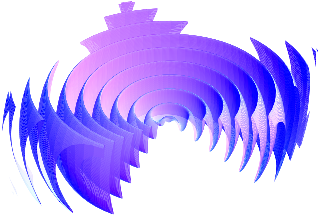
FIGURE: Link between the pulsar and its surrounding nebula.

The structure of the striped wind

Near the star :
a magnetic dipole



At large distances :
striped wind (Bogovalov 1999)



- $\vec{\Omega}$: rotation axis
- χ : magnetic axis inclination with respect to $\vec{\Omega}$
- ζ : line of sight inclination with respect to $\vec{\Omega}$

- hot and magnetized plasma in the sheet
- relativistic beaming $\Gamma_{\rm vent} \gg 1$

$\Rightarrow$ pulsed emission

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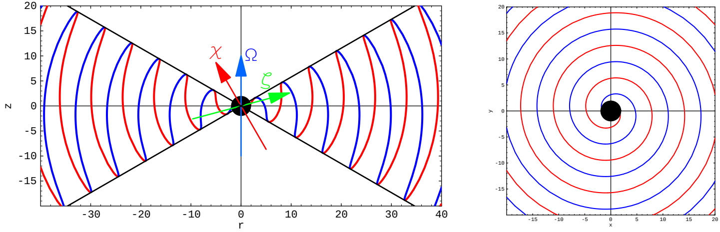
The striped wind structure

Asymptotic MHD solution : oblique rotator (Bogovalov 1999)



Properties

- assumes only $B_\varphi \propto 1/r$.
- independent of the magnetospheric structure inside the light cylinder.
- discontinuous magnetic polarity reversal
  $\Rightarrow$ infinitely thin current sheet $\equiv$ striped wind
  (more realistic model = finite thickness).

1. Objectives
   - high-energy pulsed emission (MeV/GeV)
   - spectral variability of several gamma-ray pulsars.
2. Processes
   - synchrotron radiation from hot and magnetized plasma in the stripe
   - inverse Compton with 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. Applications
   - isolated pulsars => gamma ray pulsars
   - binary pulsars => PSR B1259-63
4. Link to other wavelengths ?
   - polar cap for radio emission : phenomenological
   - striped wind for optical up to gamma rays

$\Rightarrow$ geometry could be defined (χ and ζ).

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   - synchrotron radiation from hot and magnetized plasma in the stripe

3. Applications
   - isolated pulsars => gamma ray pulsars

2. Processes
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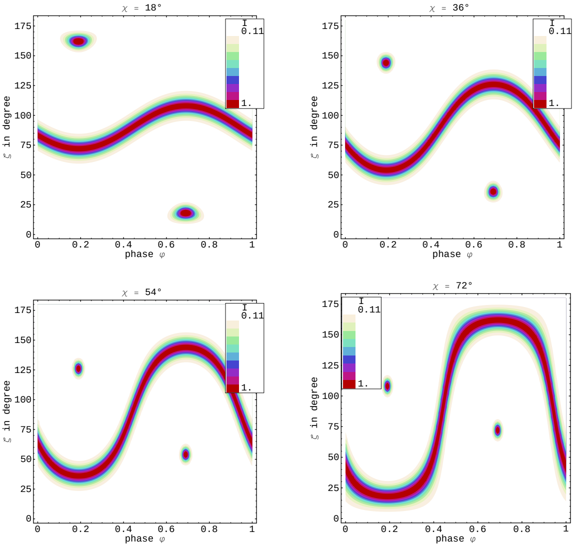
Relation between radio and gamma-ray pulses : phase-plot



(Pétri, MNRAS, 2011)

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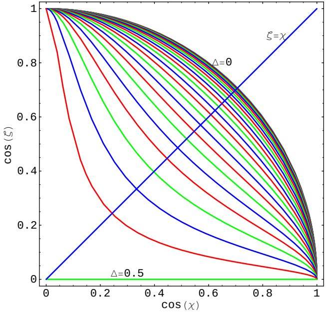
From pure geometric considerations

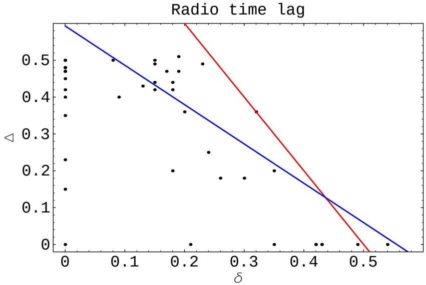
Gamma-ray peak separation Δ

$$\cos(\pi\,\Delta) = |\cot\zeta\ \cot\chi|$$

Radio time lag δ

$$\delta \approx \frac{1-\Delta}{2}$$





(Pétri, MNRAS, 2011)

Main results

- S-shape around $\zeta = 90^o$ reflects emission from current sheets
- two symmetrical spots corresponding to emission from the two polar caps (north & south pole separated by half a period)
- several light-curve combinations possible depending on geometry χ, ζ

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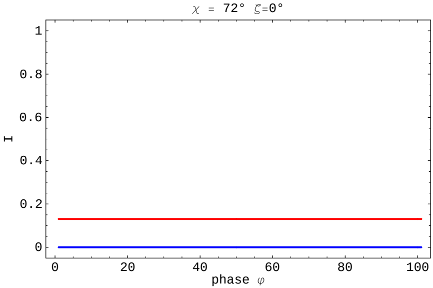
1. no radio/gamma pulse !



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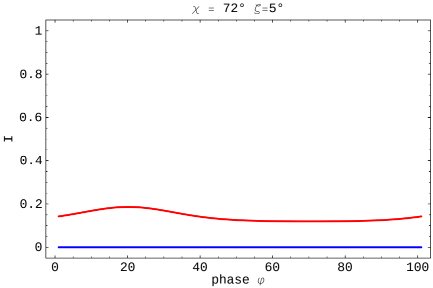

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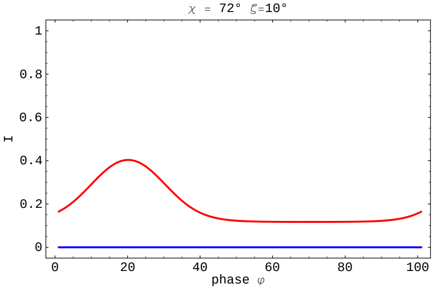

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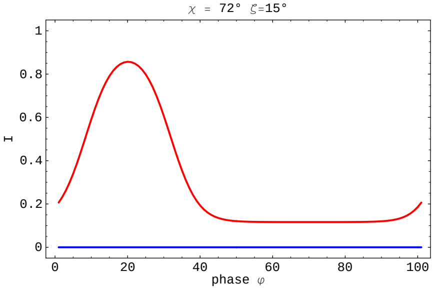

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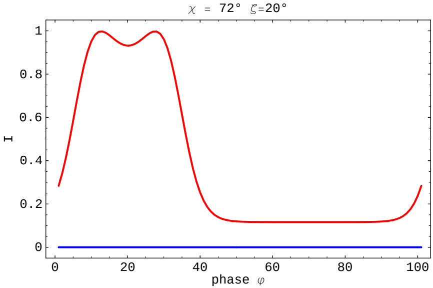

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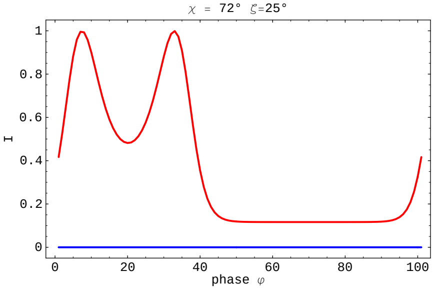

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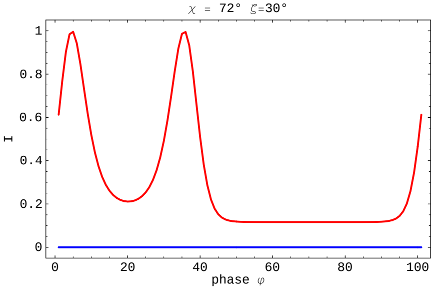

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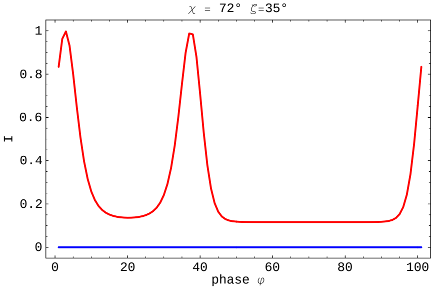

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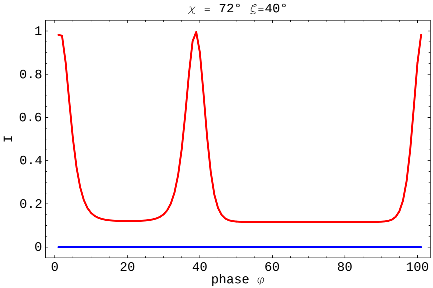

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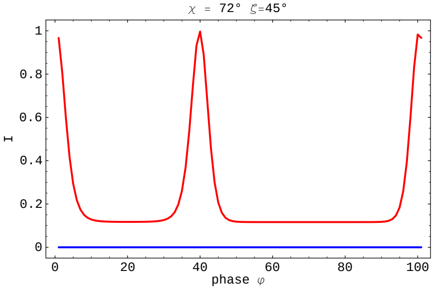

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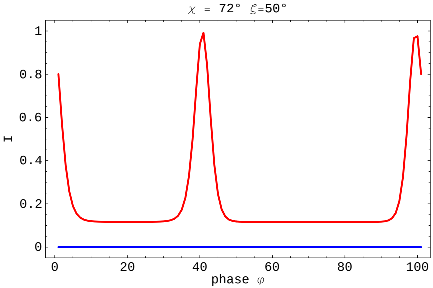

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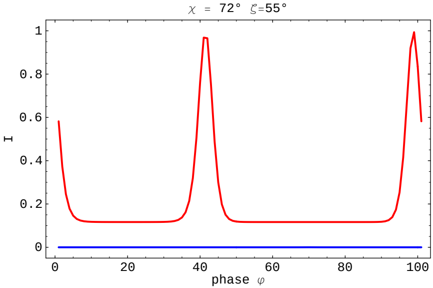

(Pétri, MNRAS, 2011)

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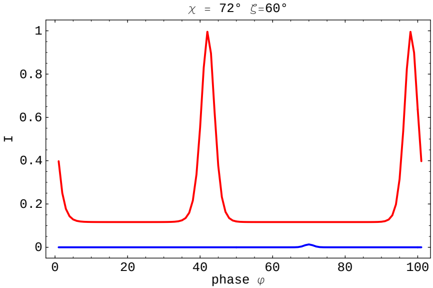

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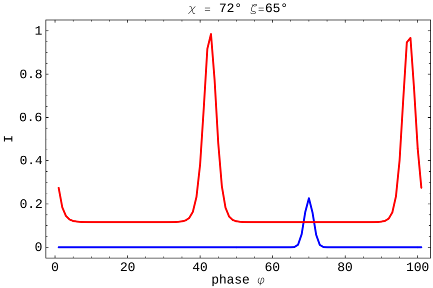

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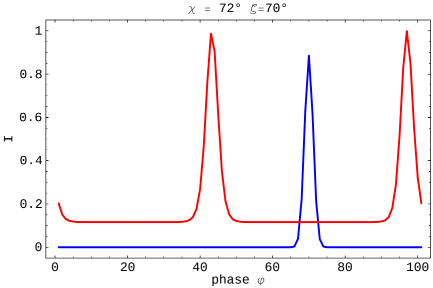

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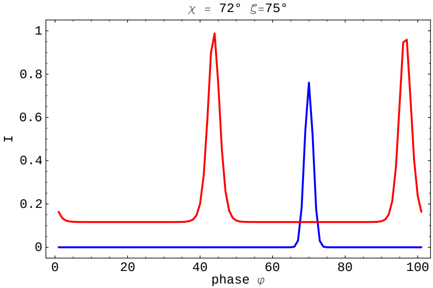

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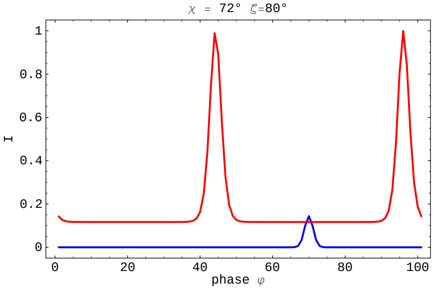

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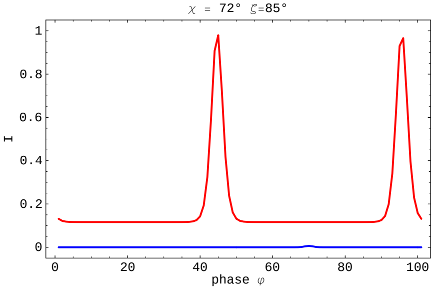

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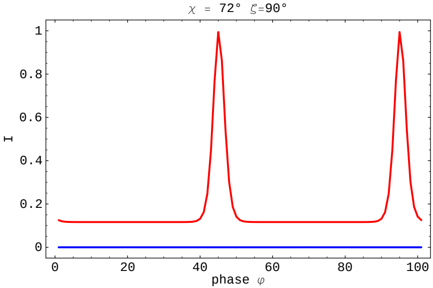

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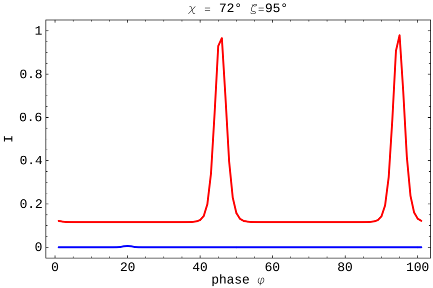

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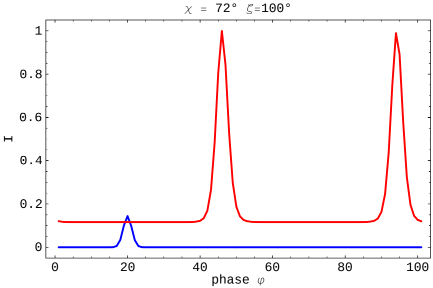

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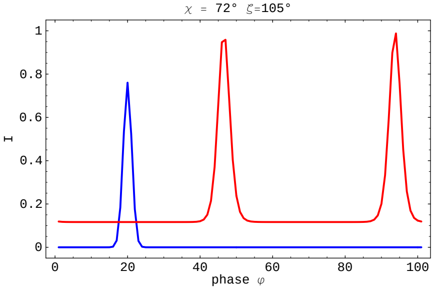

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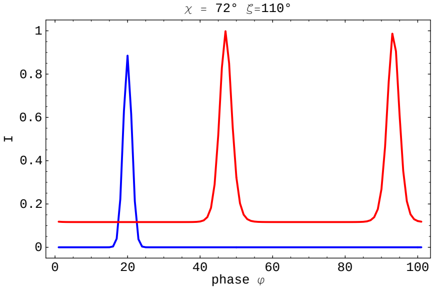

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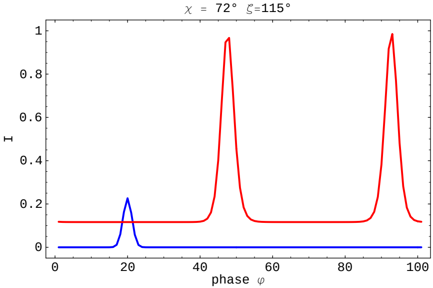

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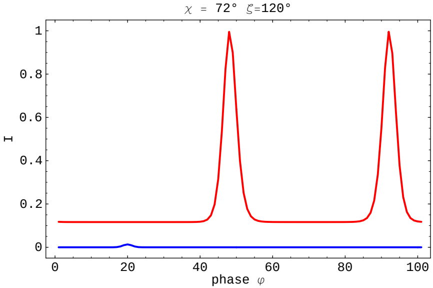

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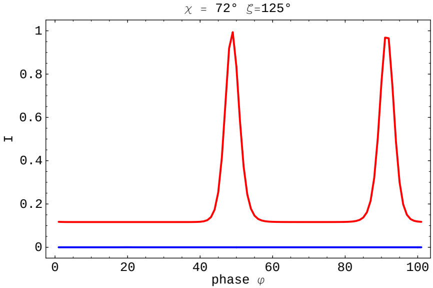

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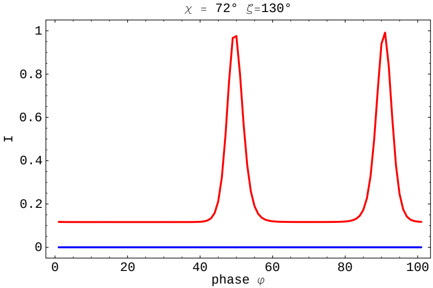

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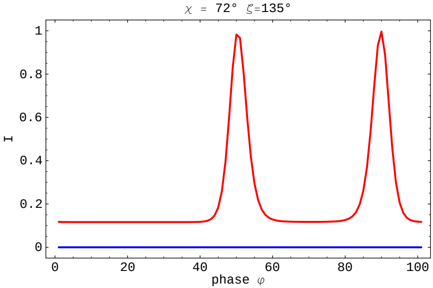

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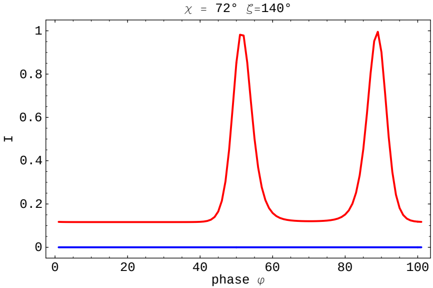

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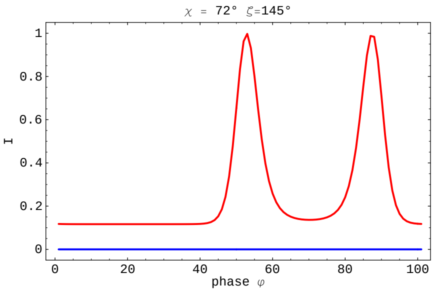

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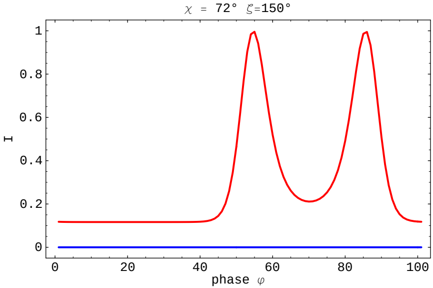

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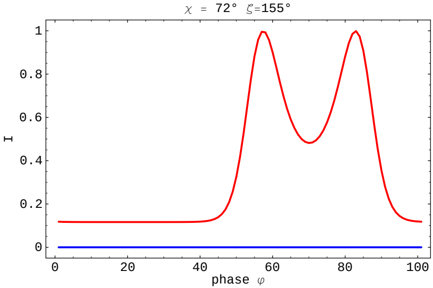

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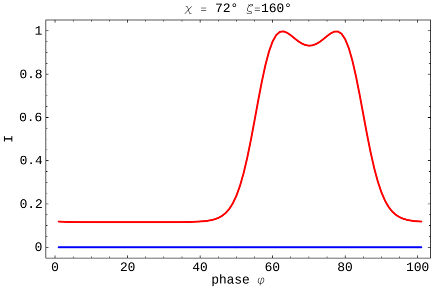

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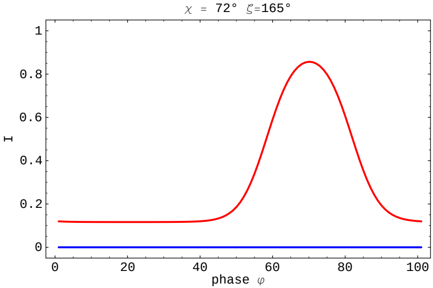

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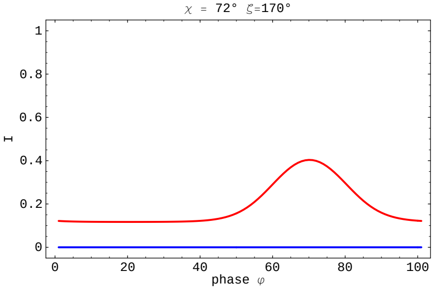

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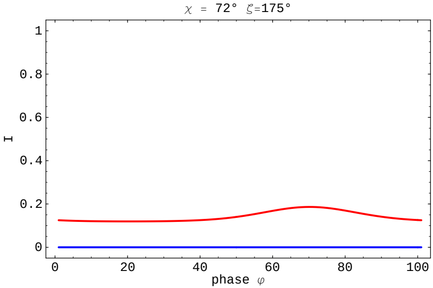

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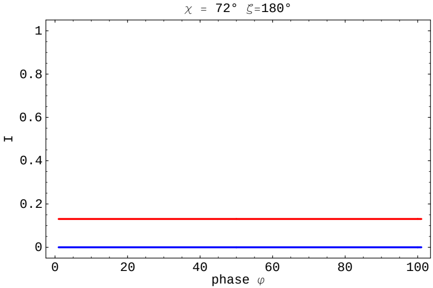

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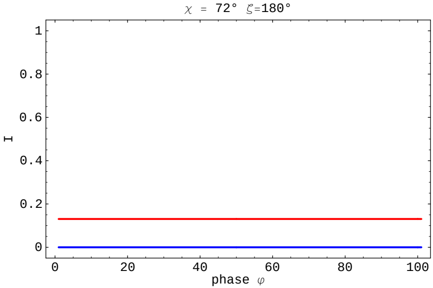
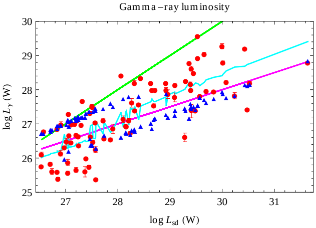
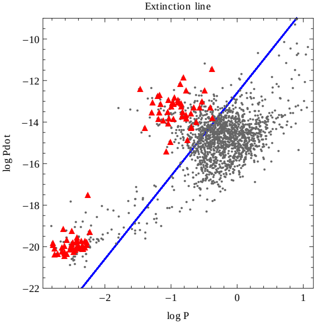
1. no radio/gamma pulse !
2. only radio
3. only gamma
4. one radio + one/two gamma-ray pulse(s)
5. two radio pulse
   => perpendicular rotator, $\zeta \approx \chi \approx 90^o$



(Pétri, MNRAS, 2011)

What about luminosities ?





Assumptions

- synchrotron emission in the stripe.
- radiative cooling compensated by reheating due to magnetic reconnection.

Main results

- the predicted luminosity function

$$L_\gamma \approx 2\times10^{26}\ \mathrm{W} \left(\frac{L_{sd}}{10^{28}\ \mathrm{W}}\right)^{1/2} \left(\frac{P}{1\ \mathrm{s}}\right)^{-1/2}$$

- condition for pulsed emission

$$\frac{L_{sd}}{P} \geq 10^{27}\ \mathrm{W/s}$$

(Pétri, MNRAS, 2012b)

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Description of the system

in the vicinity of the pulsar $r \approx r_L$ from pulsar/wind theory	in the nebula, $r \approx R_{TS}$ from PWNe theory and observations
$\sigma \approx 10^4$ and $\Gamma_v \approx 10^2$ an intense magnetic field low kinetic energy of the particles	$\sigma \ll 1$ and $\Gamma_v \approx 10^{3-6}$ a weak magnetic field ultra-relativistic particles (synchrotron radiation)
$\Rightarrow$ dynamics dominated by the electromagnetic field	the particles

A fundamental problem

- How to convert the electromagnetic energy into kinetic energy for the particles ?
- How to do the transition between the neutron star, $\sigma \gg 1$, to the nebula, $\sigma \ll 1$?

Idea

Magnetic energy dissipation/annihilation/reconnection at the termination shock of a striped wind.
Lyubarsky & Kirk (2002), Pétri & Lyubarsky (2007)

Goal

Study the mechanism of magnetic reconnection in the pulsar wind :

- acceleration of the wind.
- magnetic energy conversion into kinetic energy for the particles.

Method

- analytical and semi-analytical
  - linear study of the electromagnetic instabilities by solving numerically the linearized Vlasov-Maxwell equations.
  - find the condition for magnetic field dissipation when the wind crosses the termination shock.
- numerical : PIC simulations.

Applications

- instabilities in relativistic plasmas.
- relativistic Harris current sheet.
- striped wind.
- gamma-ray bursts.

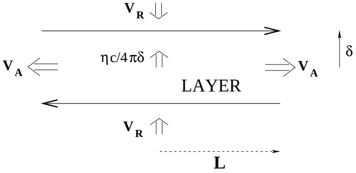
Heuristic definition

Reorganization of the magnetic field configuration because of the finite resistivity of the plasma
$\Rightarrow$ violation of the ideal MHD approximation in regions where strong $\vec{B}$ gradient exists.

Different kind of reconnection

- forced reconnection, plasma is compressed by the flow
- spontaneous reconnection, plasma is subject to an instability (tearing mode for example)

Sweet-Parker reconnection



(Parker 1957, Sweet 1958)

In the reconnecting sheet

- flux of incoming matter in the sheet (thickness δ, length L) at a speed V_R.
- incoming magnetic flux compensated by magnetic diffusion.
- outcoming flow at the Alfvèn speed V_A.
- the reconnection rate is defined by

$$
\begin{aligned}
V_R/V_A &= \delta/L = S^{-1/2} \\
S &= L\,V_A/\eta
\end{aligned}
$$

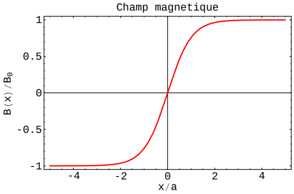
Composition of the wind

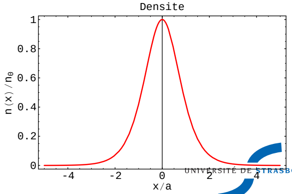
- $e^{\pm}$ pairs in drift motion equal but opposite in direction
- relativistic speeds.

Description of the structure of a stripe

Exact solution : the relativistic Harris current sheet

- magnetic field :
  $B_z(x) = B_0 \tanh(x/a)$;
- particle density of each species :
  $n(x) = N_s \,\mathrm{sech}^2(x/a)$;
- temperature :
  $\Theta = k_B T_s / m c^2$;
- distribution function of the particles :
  $f(x, \vec{p}) = \frac{n(x)}{4 \pi m^3 c^3 \Theta K_2(1/\Theta)} e^{-\Gamma_s (E \pm c \beta_s p_y)/\Theta m c^2}$.





Magnetic reconnection : kinetic approach, linearized problem

Vlasov-Maxwell equation

$$\frac{\partial f}{\partial t} + \vec{v} \cdot \frac{\partial f}{\partial \vec{r}} + q\,(\vec{E} + \vec{v} \wedge \vec{B}) \cdot \frac{\partial f}{\partial \vec{p}} = 0$$

The perturbation of f_s is computed by numerical integration of the trajectories of the particles along the equilibrium orbits. Charge and current densities are obtained by integration over the momentum (by Gauss-Hermite quadrature).

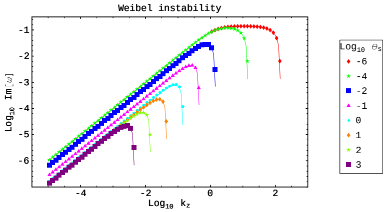
Eigenvalue system

For the electromagnetic potential $(\phi, \vec{A})$

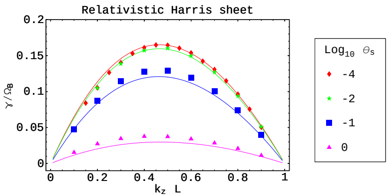
$$\begin{aligned} \phi''(x) - \left(k^2 - \frac{\omega^2}{c^2}\right) \phi(x) + \frac{\rho(x)}{\varepsilon_0} &= 0 \\ \vec{A}''(x) - \left(k^2 - \frac{\omega^2}{c^2}\right) \vec{A}(x) + \mu_0 \vec{j}(x) &= 0 \end{aligned}$$

- charge density : $\rho(x) \propto \sum_s \int_{\mathbb{R}^3} f_s(x, \vec{p})\, d^3\vec{p}$
- current density : $\vec{j}(x) \propto \sum_s \int_{\mathbb{R}^3} \vec{v}\, f_s(x, \vec{p})\, d^3\vec{p}$

Growth rate of the two-stream and tearing mode instabilities



(Pétri & Kirk, 2007a, PPCF)



(Pétri & Kirk, 2007b, PPCF)

Goal

this study should help to estimate the reconnection rate in the wind.

Principle

- striped wind structure preserved
  ⇒ Rankine-Hugoniot relations for the jump in the spatially averaged MHD quantities
  ⇒ conservation of particles, energy and momentum (over one period of the wind)
- shock region not described physically.

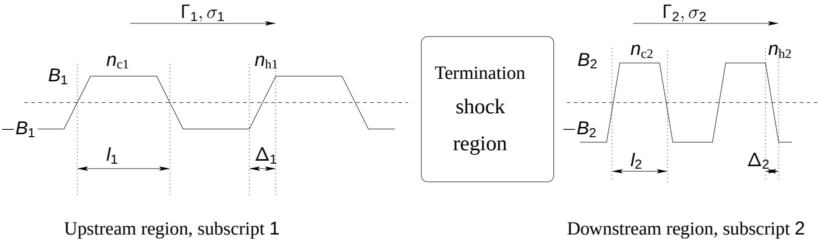
Properties

- distance between 2 current sheets l
- relative thickness of the current sheet δ
- magnetization σ
- Larmor radius r_{B}
- Lorentz factor Γ of the bulk velocity
- particle number density, "cold and hot" components, $n_{\mathrm{c}}, n_{\mathrm{h}}$

Principe

- conservation of the striped wind structure
- the shock region is not described physically.

Scheme



Only one free parameter ξ

Relates the downstream current sheet thickness to the downstream Larmor radius (subscript 2)

$$\delta_2 = \xi \, r_{B2}$$

where $\xi > 1$.

Ultra-relativistic limit $(\Gamma_1, \sigma_1) \gg 1$

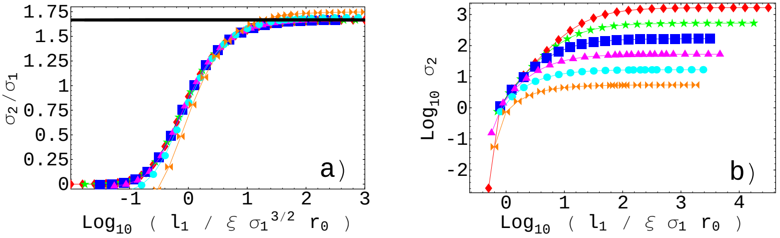
$$\delta_2 + \frac{1}{4\,\sigma_1} = \frac{1}{4\,\Gamma_2^2}$$

- for $\sigma_1 \gg \frac{5\,l_1}{\xi\, r_{B1}}$, full dissipation : $\delta_2 \approx 1, \Gamma_2 \approx 1$
- for $\sigma_1 \ll \left(\frac{5\,l_1}{4\,\xi\, r_{B1}}\right)^{2/3}$, negligible dissipation : $\delta_2 \ll 1$, $\Gamma_2 \approx \sqrt{\sigma_1} \Rightarrow$ ideal MHD

Numerical resolution

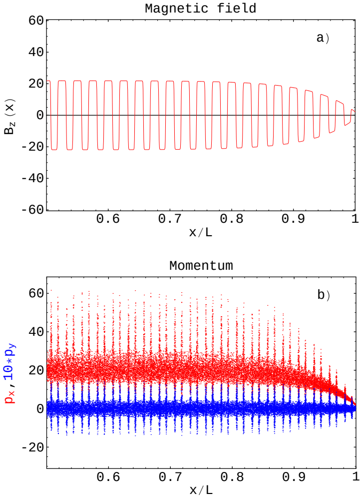
- Numerical search for the MHD jump condition in the most general case for which the upstream magnetization σ_1 is arbitrary.
- Search for the roots of a system of non-linear equations
  $\Rightarrow$ needs a good first guess for the solution (therefore the previous analytical study).

The magnetization σ_2/σ_1



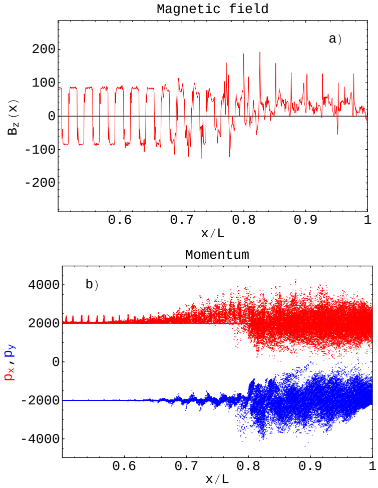
- $\sigma_2/\sigma_1 \ll 1$, almost full dissipation
- $\sigma_2/\sigma_1 \approx 2$, negligible dissipation

Example with $\sigma = 3$, $\Gamma = 20$



PIC simulations : full dissipation

Example with $\sigma = 45$, $\Gamma = 20$



(Pétri & Lyubarsky, A&A, 2007)

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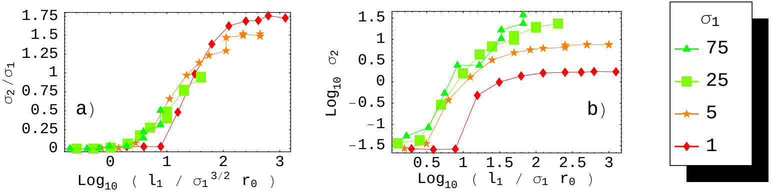
Summary of the PIC simulations



From this we deduce the parameter ξ introduced in the analytical model : $\xi \approx 10$

Magnetic reconnection at the termination shock
significant if the analytical criterion is satisfied

- for $l_1 / r_{B1} \, \sigma_1 \leq 3$, full dissipation, downstream flow purely hydrodynamical, $\Gamma_2 \approx 1$, particles heated to relativistic temperatures
- for $\sigma_1 \leq (l_1 / 12 \, r_{B1})^{2/3}$, no reconnection. Striped wind structure is preserved, simple compression, $\Gamma_2 = \sqrt{\sigma_1}$

Conclusions

Pulsed emission

- high-energy emission from the striped wind.
- luminosity in agreement with latest Fermi/LAT results.

In the wind

- magnetic reconnection important when crossing the termination shock
  - simple analytical criteria
  - confirmed by PIC simulations

In the wind

- influence of the electromagnetic precursor on the upstream flow.
- application to gamma-ray bursts and jets in active galactic nuclei : relativistic and magnetized flow (similar to pulsar winds).
- magnetic energy release into particle kinetic energy in the current sheet poorly understood.