Theory of pulsars and pulsar winds

Jérôme Pétri

Observatoire Astronomique de Strasbourg
Université de Strasbourg

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Outline

1. What we believe pulsars are ?
   - basic facts
   - orders of magnitude
2. Pulsar magnetosphere
   - an artistic view
   - phenomenological models
   - nebula : the link to the pulsar
3. Pulsar winds
   - wind structure
   - the termination shock
   - a central problem
4. Conclusions & Perspectives

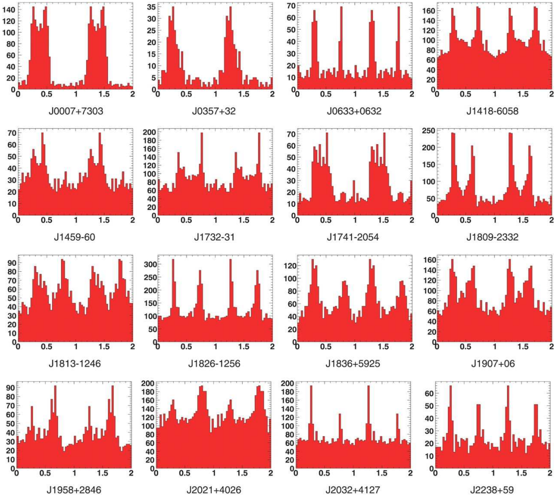
The gamma-ray pulsar fauna

- before the Fermi era, 7 gamma-ray pulsars
- since Fermi, LAT discovered 16 new pulsars
- within 8 (9) are millisecond pulsars !
- more than 50 gamma-ray pulsars known today
  $\Rightarrow$ reasonable statistic to study their general properties

Their salient spectral gamma-ray features

- power-law spectrum
  - with exponential cut-off around 1-10 GeV
  - power-law index Γ between 1 and 2
- luminosity from 10^{26} W to 10^{31} W
- flux of the order $10^{-8}\ \mathrm{photons\,cm^{-2}\,s^{-1}}$ for $E_\gamma > 100$ MeV

Gamma-ray pulsars : light-curves sample



(Abdo et al, 2009)

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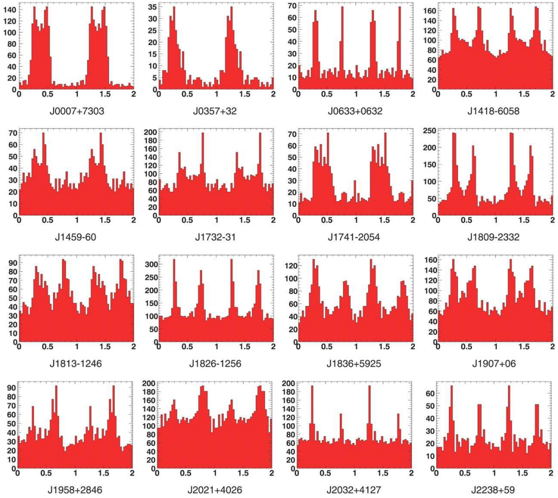

(Abdo et al, 2009)

$\Rightarrow$ Double peak structure for $\sim$75% of them

$\Rightarrow$ Where does this emission come from ?

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Pulsar magnetosphere : general picture

What is a pulsar ?

1. neutron star
   compact object $\Rightarrow$ strong gravity effects
2. strongly magnetized
   $\Rightarrow$ plasmas, QED effects (pair creation)
3. rotating
   $\Rightarrow$ huge electric fields

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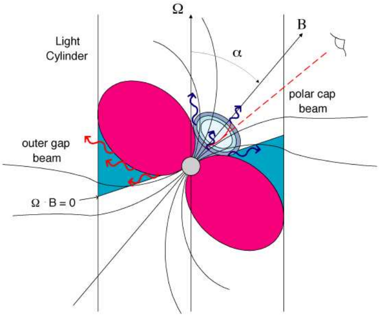

Credit : A.K. Harding

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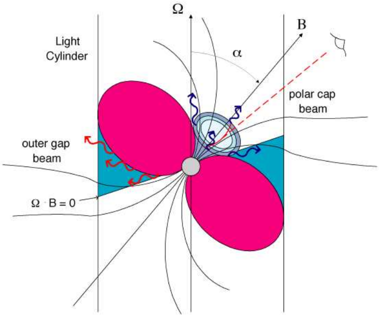


Credit : A.K. Harding

Some useful definitions

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

Pulsar magnetosphere : orders of magnitude

From observations

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

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

very different from black holes or accreting neutron stars

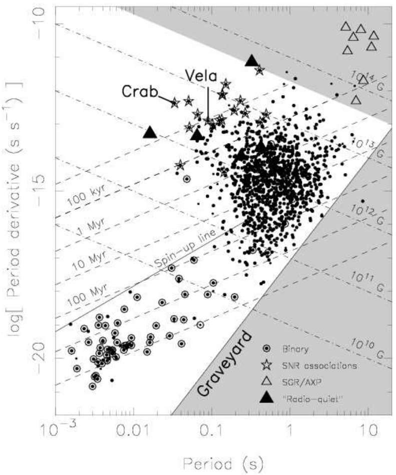
- inferred magnetic field estimate by dipole radiation

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

- huge induced electric field on crust

$$E_* = \Omega_*\,B_*\,R_* = 10^{13}\ V/m$$

$\Rightarrow$ "instantaneous" acceleration to ultra-relativistic speed, $\gamma \gg 1$ ($\tau_{\rm acc} < 10^{-20}$ s)



Credit : Lorimer & Kramer

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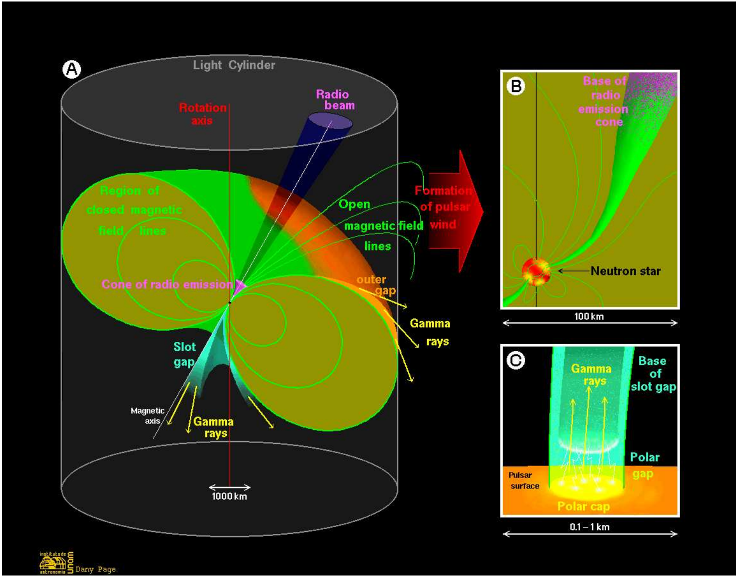
The “standard model” of a pulsar



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 ? PWN will give some clues

A problem

$\Rightarrow$ the total charge of the system is not conserved

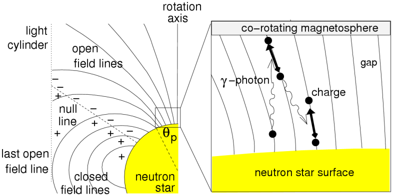
$\Rightarrow$ total electric current does not vanish !

Polar cap

Main ingredients for the recipe

- polar cap size

$$R_{\rm pc} \approx R_* \sqrt{\frac{R_*}{r_L}} \approx 145 \left(\frac{P}{1\ \mathrm{s}}\right)^{-1/2} \ \mathrm{m}$$



Credit : Lorimer & Kramer

- potential drop between centre and border of a polar cap

$$\Delta\phi = \frac{\Omega_*^2 B_* R_*^3}{c} \approx 1.3\times10^{13}\ \mathrm{V} \left(\frac{P}{1\ s}\right)^{-2} \left(\frac{B_*}{10^8\ \mathrm{T}}\right) \left(\frac{R_*}{10\ \mathrm{km}}\right)^3$$

- particle flux from one polar cap

$$\dot N_{\rm pc} = 2\,\pi\,\frac{\varepsilon_0\,\Omega_*^2 B_* R_*^3}{e} \approx 1.37\times10^{30}\ \mathrm{s}^{-1} \left(\frac{P}{1\ s}\right)^{-2} \left(\frac{B_*}{10^8\ \mathrm{T}}\right) \left(\frac{R_*}{10\ \mathrm{km}}\right)^3$$

Drawbacks

- high gamma-ray opacity due to magnetic field

Sturrock (1971), Ruderman & Sutherland (1975)

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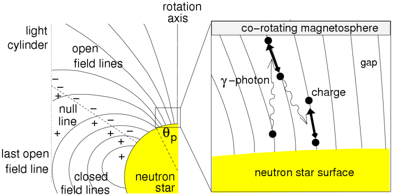

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Sturrock (1971), Ruderman & Sutherland (1975)

⇒ particle outflow generating a poynting dominated wind

Another recipe

- vacuum gaps form along the null surface (where charge density vanishes $\rho_e = 0$)
- particles escape across the light-cylinder
- no replenishment from the polar cap because opposite sign of charge
- depletion regions built up accelerating electric field $E_\parallel \neq 0$
- particle acceleration to high Lorentz factor limited by curvature radiation reaction

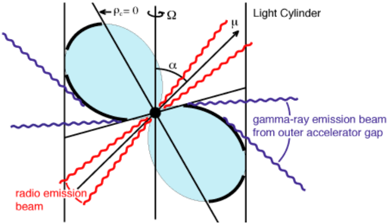
Cheng, Ho & Ruderman (1986)

Advantages

- sharp gamma-ray emission along separatrix
- geometry well constrained

Drawbacks

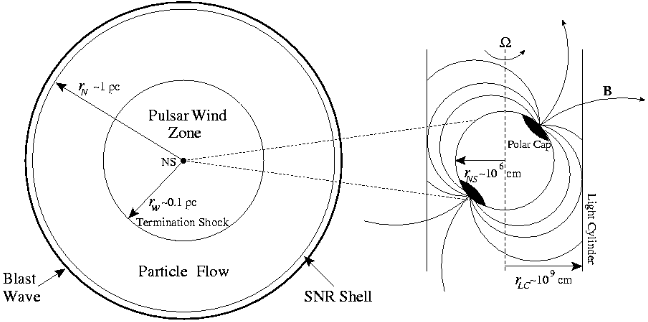
- keep $\rho_e \neq \rho_{\rm GJ}$
- $e^\pm$ pairs return to polar cap
  $\Rightarrow$ not really interesting for feeding the wind
  $\Rightarrow$ significant polar cap heating, thermal emission to high



Credit : R.W. Romani

Supernova remnant and nebula

- region I : the pulsar and its magnetosphere, source of relativistic $e^{\pm}$ pairs
- region II : ultra-relativistic cold wind flowing to the nebula
- region III : the nebula made of particles heated after crossing the MHD shock
  $\Rightarrow$ main source of radiation observed in radio, optical, X-ray and gamma-ray



From Slane

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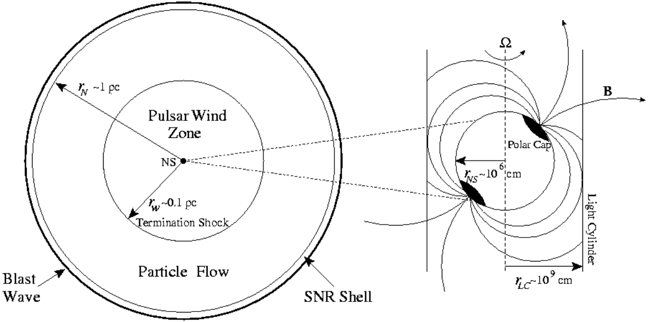

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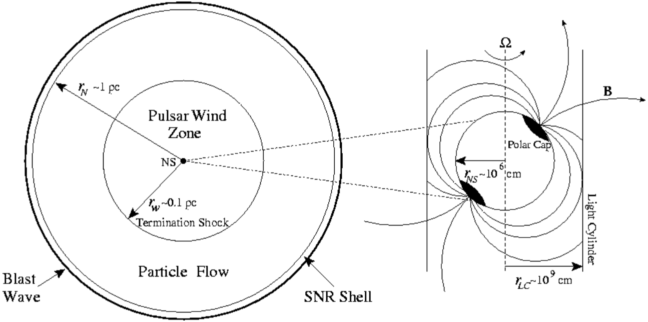

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Structure of the pulsar wind

Composition of the wind

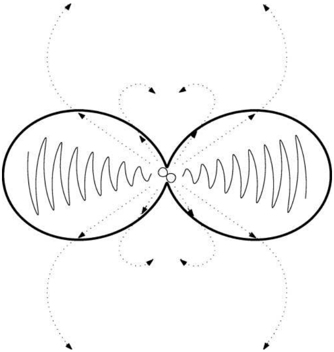
- particle acceleration in the rotating magnetosphere
- made of $e^{\pm}$ pairs, maybe ions ?

Dynamics of the wind

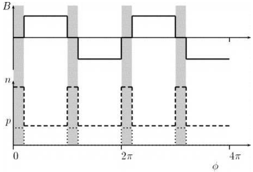
- still Poynting dominated with magnetization parameter

$$\sigma = \frac{\text{Poynting flux}}{\text{particle enthalpy flux}} = \frac{B^2}{\mu_0\,\Gamma_{\rm v}\,n\,m\,c^2} \gg 1$$

- Lorentz factor Γ_v increases until it reaches the fast magnetosonic point
- almost ballistic expansion with $\Gamma_v \gg 1$, high lorentz factor $\Gamma_v \approx 10^{2-6}$
- oblique rotator implies magnetically striped wind
- dominant azimuthal magnetic field
  $\Rightarrow$ toroidal field alternates direction
  $\Rightarrow$ current sheets, anisotropic wind



Lyubarsky (2002)



Lyubarsky & Kirk (2001)

Two distinct flows

- pulsar wind = ultra-relativistic supermagnetosonic flow
- nebula = slowly expanding plasma from $c/\sqrt{3}$ down to few 1000 km/s

$\Rightarrow$ transition through a termination shock confining the pulsar wind

Location of the termination shock

balance between ram pressure of the wind and pressure in the nebula

$$\boxed{R_{\mathrm{TS}} = \sqrt{\frac{L_{\mathrm{sd}}}{4\,\pi\,c\,P_{\mathrm{neb}}}}} \approx 0.1 - 1\ \mathrm{AU}(B \approx 10^{-7} - 10^{-5}\ \mathrm{T})$$

The termination shock is boundary between

- unshocked wind : cold magnetized upstream plasma
  $\Rightarrow$ very faint, hardly detectable
- shocked wind : hot (almost) unmagnetized downstream plasma
  $\Rightarrow$ bright synchrotron emission
- some variability seen as wisps

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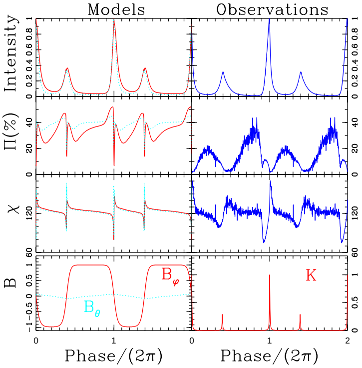
Unshocked wind

- gamma-rays by inverse Compton emission
  - CMB photons
  - synchrotron self-Compton mechanism
  - thermal X-rays from neutron star surface
  - optical-UV from companion star (in binaries)
- pulsation expected in MeV/GeV range should be detected if outside but close to the light-cylinder

$$r \lesssim \Gamma^2 r_L$$

Kirk et al (2002), Pétri (2009,2010)

- in optical, synchrotron polarization



Pétri & Kirk (2005)

Shocked wind

- TeV emission from the shocked wind

⇒ no pulsation expected at these energies (PSR B1259-63)

Kirk et al. (1999)

The wind problem

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)

A well-known pulsar/nebula association : the Crab

- emission mechanism
  = synchrotron radiation
- relativistic particles
- ordered magnetic field
  $\Rightarrow$ polarization degree high
- low equatorial magnetization
- termination shock at

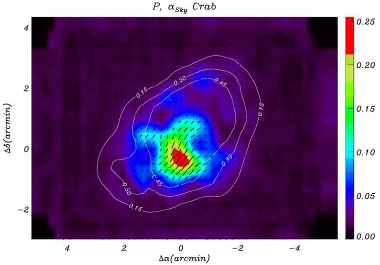
$$R_{\rm TS} = 10^8 \, r_L \approx 0.1 \, \rm pc$$

$$B \approx 10^{-8} \, \rm T$$

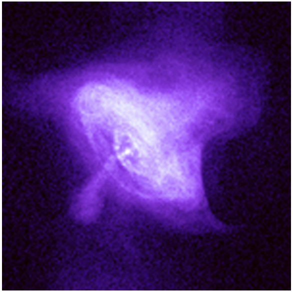
- particle injection rate

$$\dot{N}_{\rm pc} \approx 10^{40} \, \rm s^{-1}$$

pair multiplicity $\kappa \approx 10^4$
$\Rightarrow$ favors MHD against charge-separated model



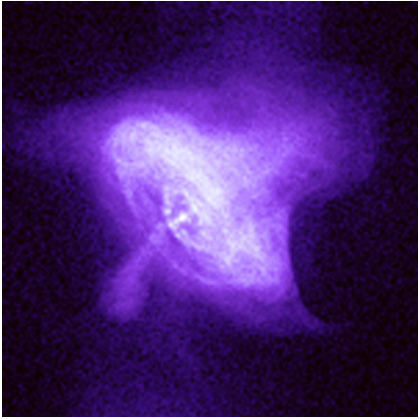
Aumont at al. (2010)



Jet/torus structure

- toroidal loops, main region of X-ray emission
- innermost ring suspected to be the termination shock
- jet/counter-jet structure close to neutron star surface $\ll R_{TS}$
- not explained by magnetic collimation $\Rightarrow$ beaming effect bright/faint jet
- but by anisotropic energy flux within the wind (cf RMHD simulations)

The Crab pulsar in X-rays



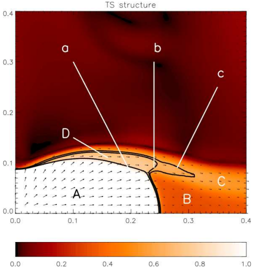
Several groups but same inputs

- relativistic MHD wind
- anisotropic Poynting energy flux (maximum at the equator)
- low magnetization in equator (stripe dissipation)

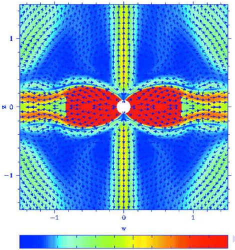
Consequences

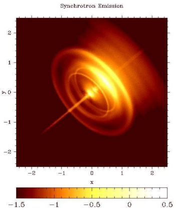
- at higher latitudes still significant B $\Rightarrow$ collimation by hoop stress
- termination shock closer to neutron at the poles than at the equator

Del Zanna et al (2006)



Komissarov & Lyubarsky (2003)





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Conclusions

Magnetosphere

- strongly magnetized rotating neutron star
- no obvious observational constrains about geometry and particle distribution
- polar cap/outer gap hard to reconcile with radio/gamma-ray observations
- lake of self-consistent global (non MHD) solution for general oblique rotator
- no simulation of particle acceleration on global scale

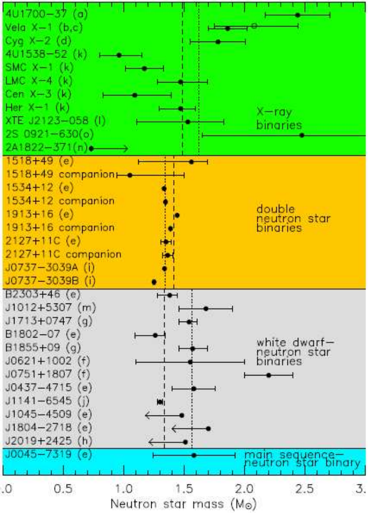
In the wind

- high Lorentz factor $\Gamma_v = 10^{2-6}$
- radial expansion with acceleration to the FMS wave speed
- anisotropic geometry
  - stripes in the equatorial region (low σ but most of energy flux)
  - polar region collimated by magnetic hoop stress
- particles accelerated at termination shock
  => non thermal emission within the nebula
- σ-paradox not solved
- composition of the wind, electrons/positrons and ions(?)

Link between outer magnetosphere and base of the wind ?
crucial because = probable site where gamma-rays come from

ANNEXES

Neutron star masses statistics



Lattimer & Prakash