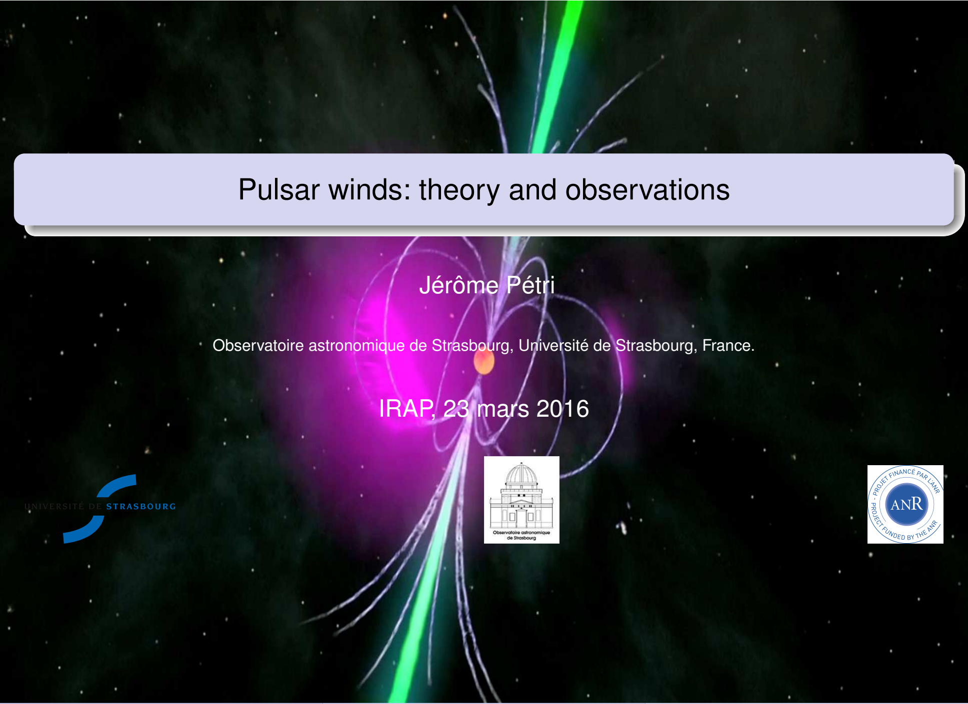


Pulsar winds: theory and observations

Jérôme Pétri

Observatoire astronomique de Strasbourg, Université de Strasbourg, France.

IRAP, 23 mars 2016

Outline

1. A brief overview
    - basic facts
    - orders of magnitude
    - high-energy emission
    - link with the nebula
2. Neutron star electrodynamics
    - “standard explanations”
    - magnetosphere simulations
    - wind structure
    - a central problem
    - striped wind
3. Conclusion & Perspectives

1 A brief overview

- basic facts
- orders of magnitude
- high-energy emission
- link with the nebula

2 Neutron star electrodynamics

- “standard explanations”
- magnetosphere simulations
- wind structure
- a central problem
- striped wind

3 Conclusion & Perspectives

1. A brief overview
   - basic facts
   - orders of magnitude
   - high-energy emission
   - link with the nebula

2. Neutron star electrodynamics
   - “standard explanations”
   - magnetosphere simulations
   - wind structure
   - a central problem
   - striped wind

3. Conclusion & Perspectives

What is a pulsar ? general magnetospheric picture

1. neutron star
   compact object ⇒ strong gravity effects

$$\xi \equiv \frac{G\,M}{R\,c^2} \approx 0.35 \tag{1}$$

2. strongly magnetized
   ⇒ plasmas, QED effects (pair creation)

$$B_q \equiv \frac{m^2\,c^2}{e\,\hbar} \approx 4.4 \times 10^9\ \mathrm{T} \tag{2}$$

3. rotating
   ⇒ huge electric fields

$$E_{\mathrm{schw}} \equiv c\,B_q \approx 1.3 \times 10^{18}\,\mathrm{V/m} \tag{3}$$

What is a pulsar ? general magnetospheric picture

1. neutron star
   compact object ⇒ strong gravity effects
   $$\xi \equiv \frac{G\,M}{R\,c^2} \approx 0.35 \tag{1}$$
2. strongly magnetized
   ⇒ plasmas, QED effects (pair creation)
   $$B_q \equiv \frac{m^2\,c^2}{e\,\hbar} \approx 4.4 \times 10^9\ \mathrm{T} \tag{2}$$
3. rotating
   ⇒ huge electric fields
   $$E_{\mathrm{schw}} \equiv c\,B_q \approx 1.3 \times 10^{18}\,\mathrm{V/m} \tag{3}$$

What is a pulsar ? general magnetospheric picture

1. **neutron star**
   compact object ⇒ strong gravity effects
   $$\xi \equiv \frac{G\,M}{R\,c^2} \approx 0.35 \qquad (1)$$
2. **strongly magnetized**
   ⇒ plasmas, QED effects (pair creation)
   $$B_q \equiv \frac{m^2\,c^2}{e\,\hbar} \approx 4.4 \times 10^9\ \mathrm{T} \qquad (2)$$
3. rotating
   ⇒ huge electric fields
   $$E_{\mathrm{schw}} \equiv c\,B_q \approx 1.3 \times 10^{18}\,\mathrm{V/m} \qquad (3)$$

What is a pulsar ? general magnetospheric picture

1. neutron star
   compact object ⇒ strong gravity effects

$$\xi \equiv \frac{G\,M}{R\,c^2} \approx 0.35 \tag{1}$$

2. strongly magnetized
   ⇒ plasmas, QED effects (pair creation)

$$B_q \equiv \frac{m^2\,c^2}{e\,\hbar} \approx 4.4 \times 10^9\ \mathrm{T} \tag{2}$$

3. rotating
   ⇒ huge electric fields

$$E_{\mathrm{schw}} \equiv c\,B_q \approx 1.3 \times 10^{18}\mathrm{V/m} \tag{3}$$

What is a pulsar ? general magnetospheric picture

1. neutron star
   compact object ⇒ strong gravity effects

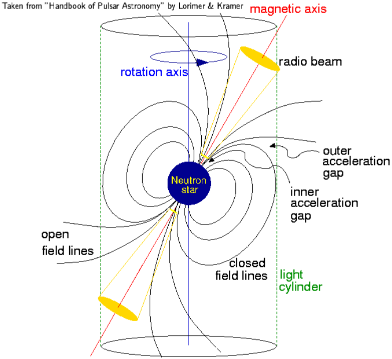
$$\xi \equiv \frac{G\,M}{R\,c^2} \approx 0.35 \tag{1}$$

2. strongly magnetized
   ⇒ plasmas, QED effects (pair creation)

$$B_q \equiv \frac{m^2\,c^2}{e\,\hbar} \approx 4.4 \times 10^9\ \mathrm{T} \tag{2}$$

3. rotating
   ⇒ huge electric fields

$$E_{\rm schw} \equiv c\,B_q \approx 1.3 \times 10^{18}\,\mathrm{V/m} \tag{3}$$



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

Credit : A.K. Harding

What is a pulsar ? general magnetospheric picture

1. neutron star
   compact object ⇒ strong gravity effects

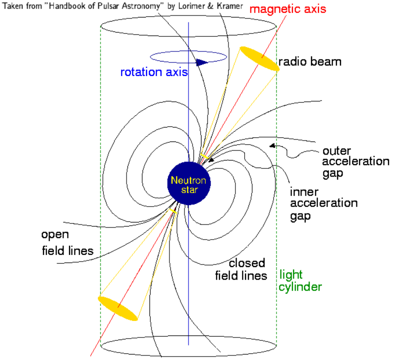
$$\xi \equiv \frac{G\,M}{R\,c^2} \approx 0.35 \tag{1}$$

2. strongly magnetized
   ⇒ plasmas, QED effects (pair creation)

$$B_q \equiv \frac{m^2\,c^2}{e\,\hbar} \approx 4.4 \times 10^9\ \mathrm{T} \tag{2}$$

3. rotating
   ⇒ huge electric fields

$$E_{\rm schw} \equiv c\,B_q \approx 1.3 \times 10^{18}\,\mathrm{V/m} \tag{3}$$



Credit : A.K. Harding

Some useful definitions

- obliquity χ : angle between magnetic moment $\vec{\mu}$ and rotation axis $\vec{\Omega}$
- 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 : $r_{\rm L} = c/\Omega$
  ⇒ transition from quasi-static to wave zone (⇒ very different plasma regimes)

Neutron star magnetospheres : orders of magnitude

- 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

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

- ⇒ consistent with magnetic flux conservation during gravitational collapse
- but no constrain on the geometry (obliquity χ)
- probably not a good guess if multipoles present.

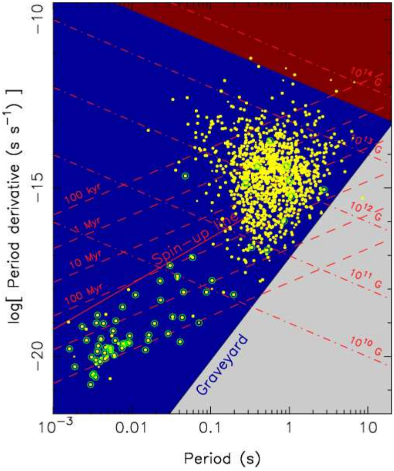


FIGURE : $P - \dot{P}$ diagramm.

Pulsar magnetosphere : orders of magnitude

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 for protons ! ! !

$$\frac{F_{\mathrm{grav}}}{F_{\mathrm{em}}} \approx \frac{G\, M\, m_p / R^2}{e\, \Omega\, B\, R} \approx 10^{-12} \ll 1 \tag{4}$$

even smaller for electrons/positrons (m_e / m_p)

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

Gamma-rays : light curves

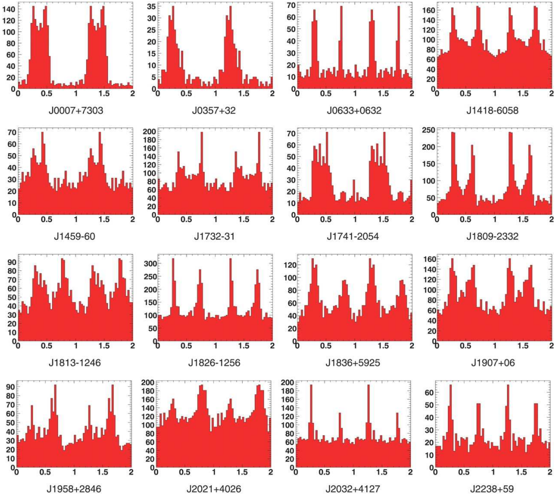


FIGURE : *Light-curves of some gamma-ray pulsars* (Abdo et al., 2009).

Gamma-rays : spectra

More than 150 gamma-ray pulsars

(a) young and energetic, visible in the whole electromagnetic spectrum (Crab).
(b) young and radio-quiet (Geminga).
(c) old (millisecond).

Essential features

- light-curves are usually double peaked (75%), separated by 0.3 in phase.
- power-law with (sub-)exponential cut-off spectra

$$\frac{dN}{dE} \propto E^{-\Gamma} \, e^{-(E/E_{\rm cut})^b}$$

$\Gamma \approx 1-2$ whereas cut-off $E_{\rm cut} \approx 1-5$ GeV and $b \leq 1$.

- cut-off gives hints on the sites of production of radiation

$\Rightarrow$ outer magnetosphere or wind ?

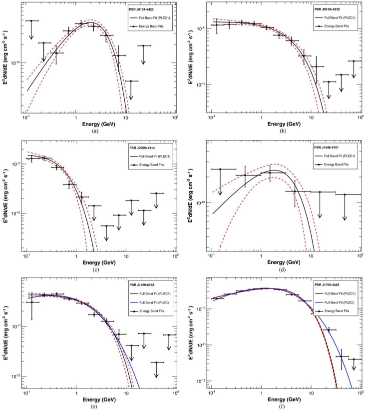


FIGURE : *Examples of spectra* (Abdo et al., 2013).

Gamma-rays : spin-down luminosity

- spin-down luminosity over many decades, $L_{\rm rot} \approx 10^{26} - 10^{31}$ W.
- gamma-ray luminosity L_γ between 0.1% and almost 100% of $L_{\rm rot}$

$\Rightarrow$ all the reservoir of rotational energy converted into photons !

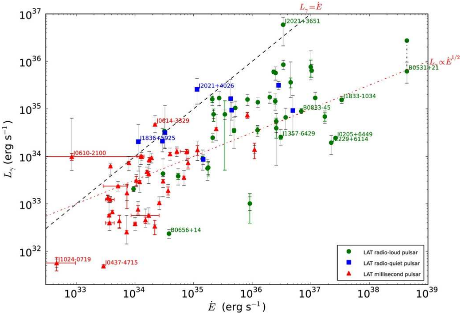


FIGURE : *Spin-down luminosity* (Abdo et al., 2013).

Gamma-rays : MeV/GeV up to TeV

- detection of pulsed emission from the Crab at 200-400 GeV
- compatible with the spectrum in the Fermi band
- spectrum as a broken power law rather than an exponential cut-off
- recent report about pulsed emission at 1.7 TeV by MAGIC

⇒ kills all existing magnetospheric emission models (opacity(TeV)$\gg$ 1) !

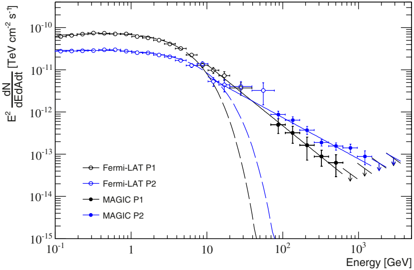


FIGURE : *MAGIC detection of Crab VHE spectrum* (Ansoldi et al., 2016).

1 A brief overview
- basic facts
- orders of magnitude
- high-energy emission
- link with the nebula

2 Neutron star electrodynamics
- “standard explanations”
- magnetosphere simulations
- wind structure
- a central problem
- striped wind

3 Conclusion & Perspectives

Supernova remnant and nebula

The pulsar linked to its surrounding nebula

- the pulsar and its magnetosphere, source of *relativistic $e^{\pm}$ pairs* $r_{\mathrm{L}} = 10^6$ m.
- the cold ultra-relativistic wind streaming to the nebula.
- the shocked wind composed of particles heated after crossing the *MHD shock*, $r_{\mathrm{ts}} = 3 \times 10^{15}$ m= 0.1 pc $\Rightarrow$ *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.*

Supernova remnant and nebula

The pulsar linked to its surrounding nebula

- the pulsar and its magnetosphere,
  source of *relativistic e$^\pm$ pairs*
  $r_{\rm L} = 10^6$ m.
- the cold ultra-relativistic wind
  streaming to the nebula.
- the shocked wind composed of particles heated after crossing the *MHD shock*, $r_{\rm ts} = 3 \times 10^{15}$ m$=$ 0.1 pc
  $\Rightarrow$ *main source of radiation* observed in radio, optics, X-rays and gamma-rays.
- the supernova remnant.
- the interstellar medium.

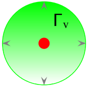


FIGURE : *Link between the pulsar and its surrounding nebula.*

Supernova remnant and nebula

The pulsar linked to its surrounding nebula

- the pulsar and its magnetosphere, source of *relativistic e$^\pm$ pairs* $r_{\rm L} = 10^6$ m.
- the cold ultra-relativistic wind streaming to the nebula.
- the shocked wind composed of particles heated after crossing the *MHD shock*, $r_{\rm ts} = 3 \times 10^{15}$ m$=$ 0.1 pc $\Rightarrow$ *main source of radiation* observed in radio, optics, X-rays and gamma-rays.
- the supernova remnant.
- the interstellar medium.

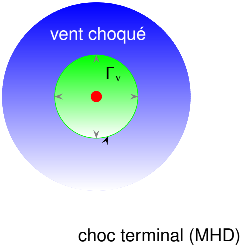
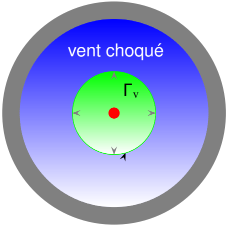


FIGURE : *Link between the pulsar and its surrounding nebula.*

Supernova remnant and nebula

The pulsar linked to its surrounding nebula

- the pulsar and its magnetosphere, source of *relativistic e$^{\pm}$ pairs* $r_{\rm L} = 10^6$ m.
- the cold ultra-relativistic wind streaming to the nebula.
- the shocked wind composed of particles heated after crossing the *MHD shock*, $r_{\rm ts} = 3 \times 10^{15}$ m$=$ 0.1 pc $\Rightarrow$ *main source of radiation* observed in radio, optics, X-rays and gamma-rays.
- the supernova remnant.
- the interstellar medium.



choc terminal (MHD)

FIGURE : *Link between the pulsar and its surrounding nebula.*

Supernova remnant and nebula

The pulsar linked to its surrounding nebula

- the pulsar and its magnetosphere, source of *relativistic e$^{\pm}$ pairs* $r_{\rm L} = 10^6$ m.
- the cold ultra-relativistic wind streaming to the nebula.
- the shocked wind composed of particles heated after crossing the *MHD shock*, $r_{\rm ts} = 3 \times 10^{15}$ m$=$ 0.1 pc $\Rightarrow$ *main source of radiation* observed in radio, optics, X-rays and gamma-rays.
- the supernova remnant.
- the interstellar medium.

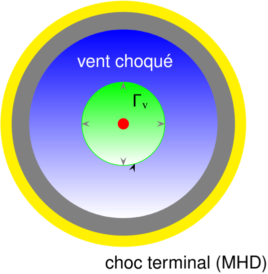


FIGURE : *Link between the pulsar and its surrounding nebula.*

Supernova remnant and nebula

The pulsar linked to its surrounding nebula

- the pulsar and its magnetosphere, source of *relativistic e$^\pm$ pairs* $r_\mathrm{L} = 10^6$ m.
- the cold ultra-relativistic wind streaming to the nebula.
- the shocked wind composed of particles heated after crossing the *MHD shock*, $r_\mathrm{ts} = 3 \times 10^{15}$ m$=$ 0.1 pc $\Rightarrow$ *main source of radiation* observed in radio, optics, X-rays and gamma-rays.
- the supernova remnant.
- the interstellar medium.

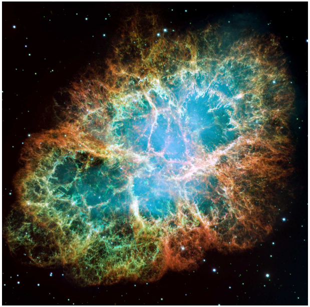


FIGURE : *The Crab nebula.*

Supernova remnant and nebula

The pulsar linked to its surrounding nebula

- the pulsar and its magnetosphere, source of *relativistic $e^{\pm}$ pairs* $r_{\rm L} = 10^6$ m.
- the cold ultra-relativistic wind streaming to the nebula.
- the shocked wind composed of particles heated after crossing the *MHD shock*, $r_{\rm ts} = 3 \times 10^{15}$ m$=$ 0.1 pc $\Rightarrow$ *main source of radiation* observed in radio, optics, X-rays and gamma-rays.
- the supernova remnant.
- the interstellar medium.

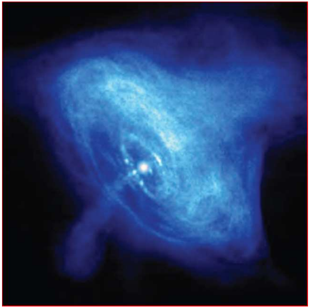


FIGURE : *The Crab nebula.*

The termination shock

Two distinct flows

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

⇒ 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 the boundary between

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

1. A brief overview
   - basic facts
   - orders of magnitude
   - high-energy emission
   - link with the nebula

2. Neutron star electrodynamics
   - “standard explanations”
   - magnetosphere simulations
   - wind structure
   - a central problem
   - striped wind

3. Conclusion & Perspectives

1 A brief overview
- basic facts
- orders of magnitude
- high-energy emission
- link with the nebula

2 Neutron star electrodynamics
- “standard explanations”
- magnetosphere simulations
- wind structure
- a central problem
- striped wind

3 Conclusion & Perspectives

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

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

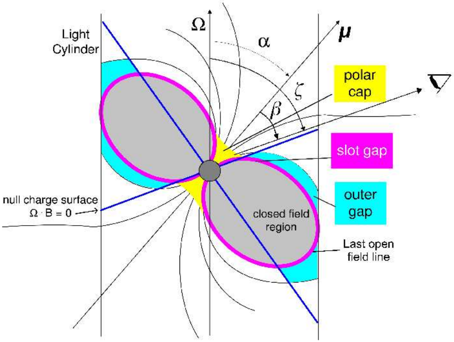
- no pressure : cold plasma.

Two interpretations

- charge-separated plasma ⇒ low particle density.
- MHD model ⇒ quasi-neutral plasma, high particle density.

Who is right ? PWN will give some clues.

Possible sites for pulsed emission : basic picture



(Credit : Breed et al)

- magnetosphere filled with $e^{\pm}$ plasma corotating with the neutron star up to the light-cylinder
- corotation charge $\rho_{\rm GJ} = -2\,\varepsilon_0\,\vec{\Omega}\cdot\vec{B}$
- no acceleration in regions where $\rho = \rho_{\rm GJ}$ because $E_{\|} = 0$
- but acceleration in regions where $\rho \neq \rho_{\rm GJ}$ because $E_{\|} \neq 0$ (cap,gap)
- formation of gaps with their own dynamics (pairs, cascade)

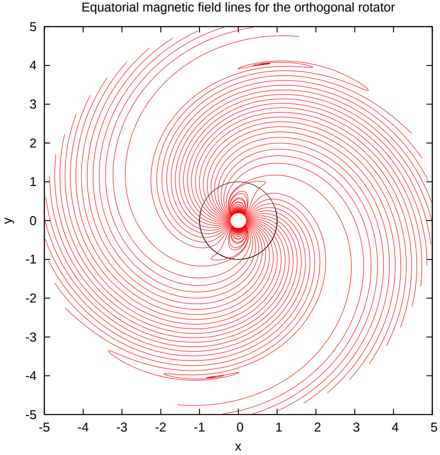
Four important sites

- polar cap : star surface R
- outer gap : inside/close to $r_{\rm L}$
- slot gap : from R to $r_{\rm L}$
- striped wind : outside $r_{\rm L}$

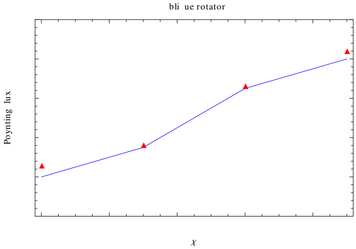
Location of gaps tells you where emission comes from
Need to know global electrodynamics of the magnetosphere

Force-free magnetospheres

Simplest approach to the pulsar electrodynamics
ideal MHD without particle inertia and without radiation



Perpendicular rotator $\chi = 90^o$

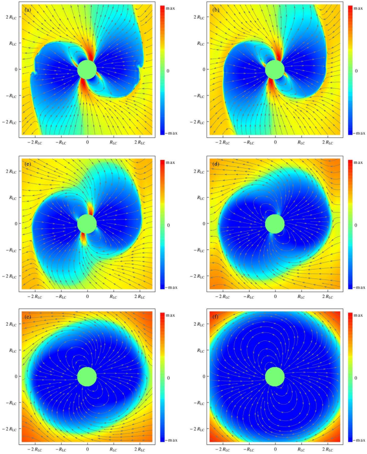


Spin-down luminosity vs χ

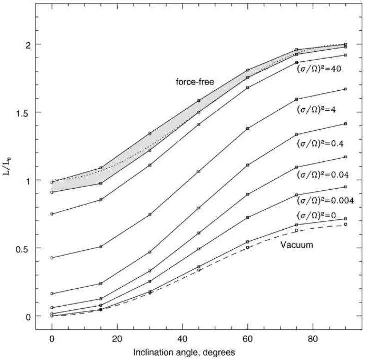
$$L_{\rm sp}^{ffe} \approx \frac{3}{2} L_{\perp}^{\rm vac} \, (1 + \sin^2 \chi)$$

Dissipative/resistive magnetospheres

Tells you where magnetic energy is dissipated into radiation.
⇒ Should trace the location of the gaps



From FFE to vacuum

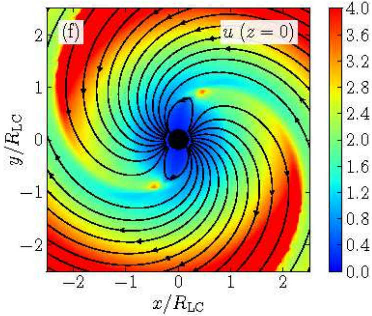


Spin-down luminosity

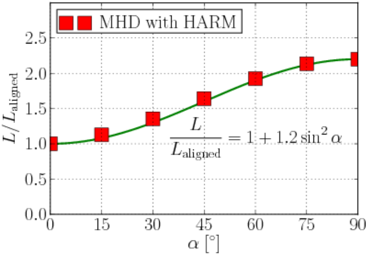
(Li et al., 2012)

MHD magnetospheres

Includes particle inertia but not particle acceleration



Perpendicular rotator $\chi = 90^o$

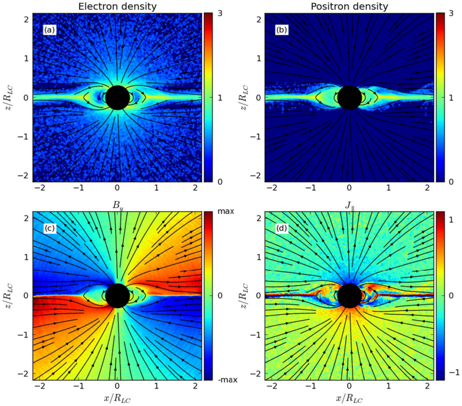


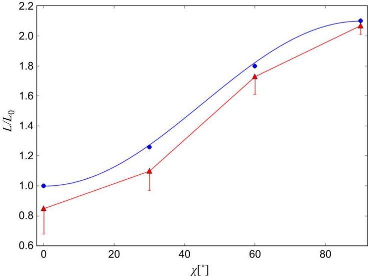
Spin-down luminosity vs χ and σ

(Tchekhovskoy et al., 2013)

PIC magnetospheres

Includes particle inertia AND particle acceleration self-consistently



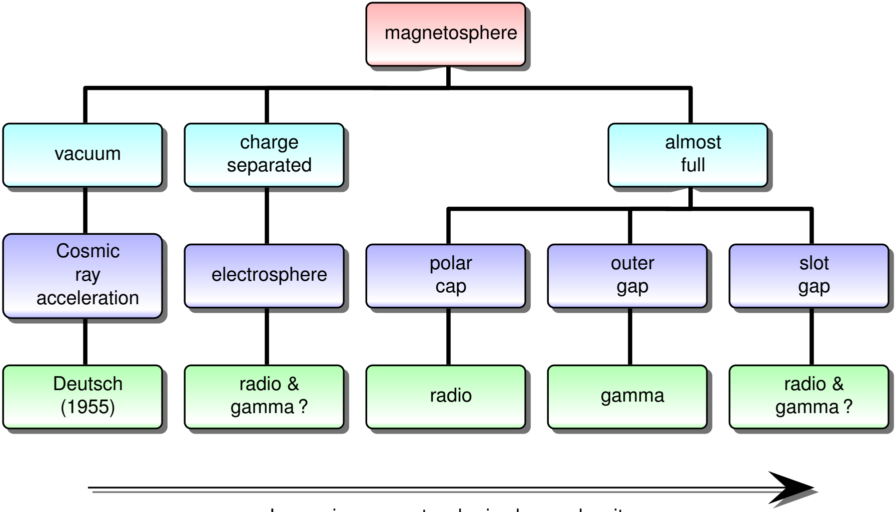


Aligned rotator $\chi = 0^o$

Spin-down luminosity

(Philippov et al., 2015)

Magnetospheric structures



Increasing magnetospheric plasma density

FIGURE : *Synthetic view of pulsar magnetosphere models.*

1 A brief overview
- basic facts
- orders of magnitude
- high-energy emission
- link with the nebula

2 Neutron star electrodynamics
- “standard explanations”
- magnetosphere simulations
- wind structure
- a central problem
- striped wind

3 Conclusion & Perspectives

Structure of the pulsar wind

Composition of the wind

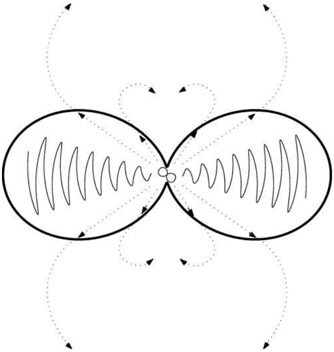
- particle acceleration in the rotating magnetosphere
- made of $e^{\pm}$ pairs, maybe ions ?

Dynamics of the wind

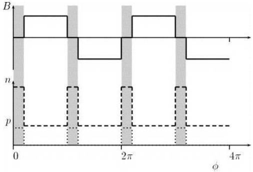
- still Poynting dominated with magnetization parameter

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

- 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



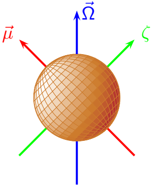
(Lyubarsky, 2002)



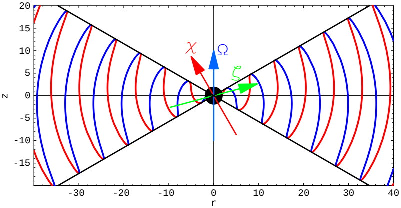
(Lyubarsky & Kirk, 2001)

Outside the magnetosphere : the striped wind

Near the star :
a rotating magnetic dipole



At large distances :
a relativistic striped wind



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

Presence of a current sheet wobbling around the equatorial plane.

$$\left.\begin{array}{l}\text{- hot and magnetized plasma in the sheet} \\ \text{- relativistic beaming } \Gamma_{\rm vent} \gg 1\end{array}\right\} \Rightarrow \text{pulsed emission}$$

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.

`(Pétri & Lyubarsky, 2007; Sironi & Spitkovsky, 2011; Porth et al., 2014)`

1. A brief overview
   - basic facts
   - orders of magnitude
   - high-energy emission
   - link with the nebula

2. Neutron star electrodynamics
   - “standard explanations”
   - magnetosphere simulations
   - wind structure
   - a central problem
   - striped wind

3. Conclusion & Perspectives

Advantages of the striped wind

- possible explanation for the σ problem : dissipation of the magnetic field into particle bulk flow and thermal motion (Pétri & Lyubarsky, 2007; Kirk et al., 2009; Sironi & Spitkovsky, 2011).
- presence of current sheets subject to tearing instability (Hesse & Zenitani, 2007).
- optical polarization of the Crab pulsar (Pétri & Kirk, 2005).
- gamma-ray pulsar emission as reported by Fermi/LAT (Abdo et al., 2013; Petri, 2012)
- possibility for pulsed synchrotron self-Compton emission up to TeV (Mochol & Pétri, 2015).
- possible explanation for Crab (nebula ?) gamma-ray flares (Takamoto et al., 2015; Pétri et al., 2015).

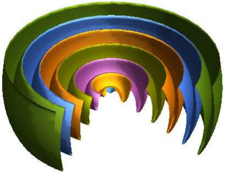


FIGURE : *Current sheet in the wind.*

Advantages of the striped wind

- possible explanation for the σ problem : dissipation of the magnetic field into particle bulk flow and thermal motion (Pétri & Lyubarsky, 2007; Kirk et al., 2009; Sironi & Spitkovsky, 2011).
- presence of current sheets subject to tearing instability (Hesse & Zenitani, 2007).
- optical polarization of the Crab pulsar (Pétri & Kirk, 2005).
- gamma-ray pulsar emission as reported by Fermi/LAT (Abdo et al., 2013; Petri, 2012)
- possibility for pulsed synchrotron self-Compton emission up to TeV (Mochol & Pétri, 2015).
- possible explanation for Crab (nebula ?) gamma-ray flares (Takamoto et al., 2015; Pétri et al., 2015).

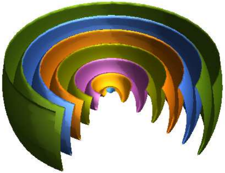


FIGURE : *Current sheet in the wind.*

Advantages of the striped wind

- possible explanation for the σ problem : dissipation of the magnetic field into particle bulk flow and thermal motion (Pétri & Lyubarsky, 2007; Kirk et al., 2009; Sironi & Spitkovsky, 2011).
- presence of current sheets subject to tearing instability (Hesse & Zenitani, 2007).
- optical polarization of the Crab pulsar (Pétri & Kirk, 2005).
- gamma-ray pulsar emission as reported by Fermi/LAT (Abdo et al., 2013; Petri, 2012)
- possibility for pulsed synchrotron self-Compton emission up to TeV (Mochol & Pétri, 2015).
- possible explanation for Crab (nebula ?) gamma-ray flares (Takamoto et al., 2015; Pétri et al., 2015).

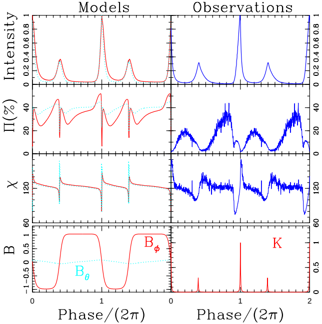


FIGURE : *Theory versus observation of the Crab (Pétri & Kirk, 2005).*

Advantages of the striped wind

- possible explanation for the σ problem : dissipation of the magnetic field into particle bulk flow and thermal motion (Pétri & Lyubarsky, 2007; Kirk et al., 2009; Sironi & Spitkovsky, 2011).
- presence of current sheets subject to tearing instability (Hesse & Zenitani, 2007).
- optical polarization of the Crab pulsar (Pétri & Kirk, 2005).
- gamma-ray pulsar emission as reported by Fermi/LAT (Abdo et al., 2013; Petri, 2012)
- possibility for pulsed synchrotron self-Compton emission up to TeV (Mochol & Pétri, 2015).
- possible explanation for Crab (nebula ?) gamma-ray flares (Takamoto et al., 2015; Pétri et al., 2015).

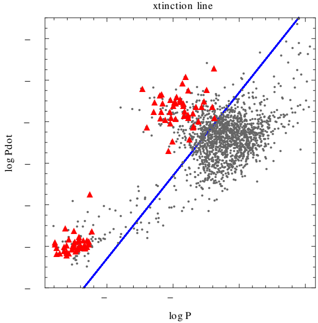


FIGURE : *Gamma-ray pulsar (Petri, 2012).*

Advantages of the striped wind

- possible explanation for the σ problem : dissipation of the magnetic field into particle bulk flow and thermal motion (Pétri & Lyubarsky, 2007; Kirk et al., 2009; Sironi & Spitkovsky, 2011).
- presence of current sheets subject to tearing instability (Hesse & Zenitani, 2007).
- optical polarization of the Crab pulsar (Pétri & Kirk, 2005).
- gamma-ray pulsar emission as reported by Fermi/LAT (Abdo et al., 2013; Petri, 2012)
- possibility for pulsed synchrotron self-Compton emission up to TeV (Mochol & Pétri, 2015).
- possible explanation for Crab (nebula ?) gamma-ray flares (Takamoto et al., 2015; Pétri et al., 2015).

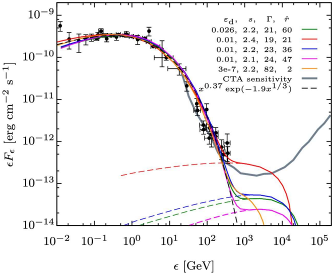


FIGURE : *VHE pulsed emission (Mochol & Pétri, 2015).*

Advantages of the striped wind

- possible explanation for the σ problem : dissipation of the magnetic field into particle bulk flow and thermal motion (Pétri & Lyubarsky, 2007; Kirk et al., 2009; Sironi & Spitkovsky, 2011).
- presence of current sheets subject to tearing instability (Hesse & Zenitani, 2007).
- optical polarization of the Crab pulsar (Pétri & Kirk, 2005).
- gamma-ray pulsar emission as reported by Fermi/LAT (Abdo et al., 2013; Petri, 2012)
- possibility for pulsed synchrotron self-Compton emission up to TeV (Mochol & Pétri, 2015).
- possible explanation for Crab (nebula ?) gamma-ray flares (Takamoto et al., 2015; Pétri et al., 2015).

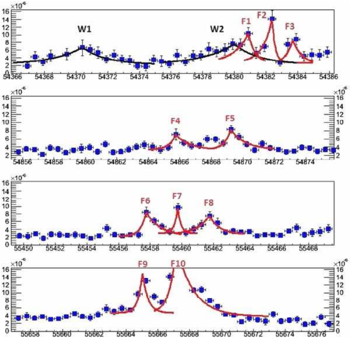


FIGURE : *Temporal evolution of the Crab flares seen in gamma-rays (Striani et al., 2013).*

1. A brief overview
   - basic facts
   - orders of magnitude
   - high-energy emission
   - link with the nebula

2. Neutron star electrodynamics
   - “standard explanations”
   - magnetosphere simulations
   - wind structure
   - a central problem
   - striped wind

3. Conclusion & Perspectives

Conclusions & Perspectives

Theory of pulsar magnetospheres

- global structure of the magnetosphere well constraint
- linked to the striped wind.

⇒ strongly magnetized ultra-relativistic outflow $\Gamma, \sigma \gg 1$.

- some dissipation regions required for acceleration/emission : FIDO

⇒ acceleration of particles through MHD/PIC simulations

- more realistic assumptions for the plasma

⇒ relaxation of the force-free condition : dissipation, resistivity, radiation reaction.

Open issues

- composition of the wind : electrons/positrons and protons/ions ?
- bulk flow acceleration mechanism ?
- σ problem : how and where to dissipate magnetic energy ?
- particle acceleration at the termination shock : why a power law ?

References I

Abdo A. A. et al., 2009, Science, 325, 840

Abdo A. A. et al., 2013, ApJS, 208, 17

Ansoldi S. et al., 2016, A&A, 585, A133

Hesse M., Zenitani S., 2007, Physics of Plasmas, 14, 112102

Kirk J. G., Lyubarsky Y., Petri J., 2009, Astrophysics and Space Science Library, 357, 421

Li J., Spitkovsky A., Tchekhovskoy A., 2012, ApJ, 746, 60

Lyubarsky Y., Kirk J. G., 2001, ApJ, 547, 437

Lyubarsky Y. E., 2002, MNRAS, 329, L34

Mochol I., Pétri J., 2015, MNRAS, 449, L51

Petri J., 2012, MNRAS, 424, 2023

Pétri J., 2012, MNRAS, 424, 605

Pétri J., Kirk J. G., 2005, ApJL, 627, L37

Pétri J., Lyubarsky Y., 2007, A&A, 473, 683

Pétri J., Takamoto M., Baty H., Zenitani S., 2015, Plasma Physics and Controlled Fusion, 57, 014034

References II

Philippov A. A., Spitkovsky A., Cerutti B., 2015, ApJL, 801, L19

Porth O., Komissarov S. S., Keppens R., 2014, MNRAS, 438, 278

Sironi L., Spitkovsky A., 2011, ApJ, 741, 39

Spitkovsky A., 2006, ApJL, 648, L51

Striani E. et al., 2013, ApJ, 765, 52

Takamoto M., Pétri J., Baty H., 2015, MNRAS, 454, 2972

Tchekhovskoy A., Spitkovsky A., Li J. G., 2013, MNRAS, 435, L1