The pulsars’magnetospheres

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Fabrice Mottez,

très redevable à Jérôme Pétri (Obs. Strasbourg)

qui a fourni un matériel abondant

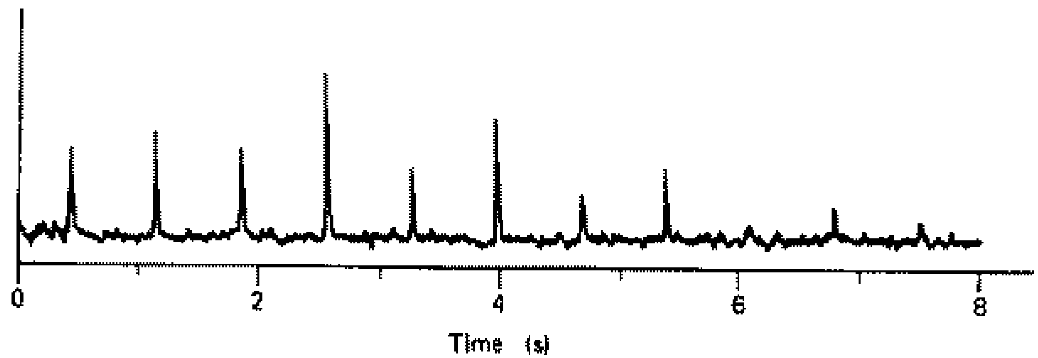
dérivé de sa présentation à Cargèse en 2005

Laboratoire Univers et THéories (LUTH) - Obs. Paris-Meudon - CNRS - Univ. Paris Diderot

Discovery

First pulsar discovered fortuitously at Cambridge Observatory in 1967:

Radio signal measured from PSR1919+21 (Bell & Hewish, 1968)



- signal made of a series of pulses separated by a period $P = 1.337$ s ;
- pulse profile changes randomly but arrival time stable in time $\Rightarrow$ rotational effect.
- duration of a pulse $\Delta t \approx$ 16 ms
  $\Rightarrow$ size of the emitting region: $L \leq c\,\Delta t \approx 4800$ km
  $\Rightarrow$ Gravitation/rotation coherence: $L \sim 10 - 100$km. Too small for a white dwarf.

Pulsar = strongly magnetised rotating neutron star.

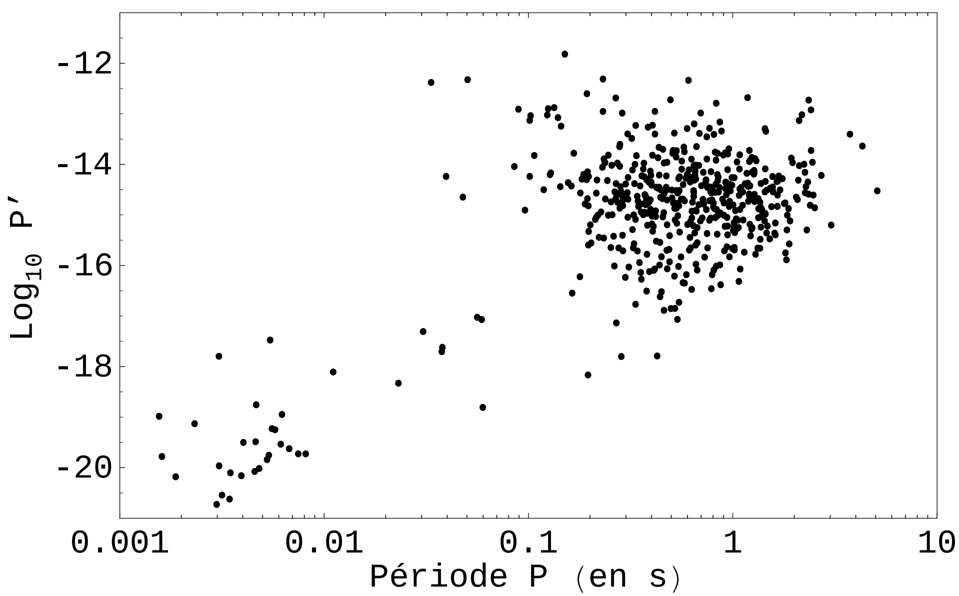
Typical neutron star parameters

- mass $M_* = 1.4\,M_\odot$;
- radius $R_* = 10\,\mathrm{km}$ ($R_\odot = 700.000\,\mathrm{km}$) ;
- mean density $\rho_* = 10^{17}\,\mathrm{kg/m^3}$ ($\rho_\odot = 1.410\,\mathrm{kg/m^3}$) ;
- crust temperature $T_* = 10^6$ K ;
- moment of inertia $I_* = 10^{38}\ \mathrm{kg\,m^2}$;

Observations: general aspects

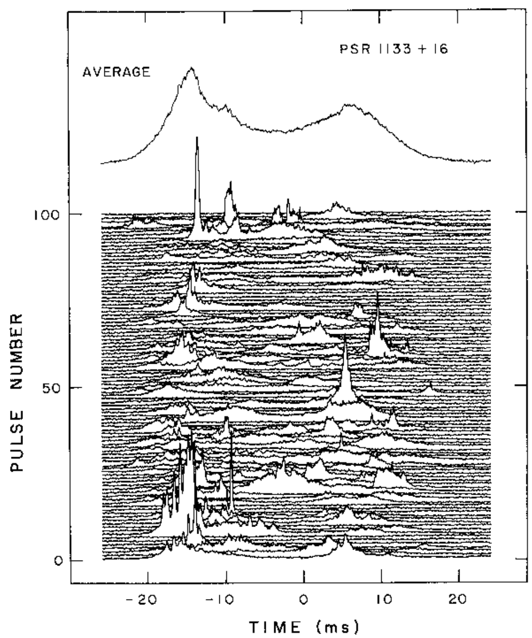
- to date about 2000 pulsars are known ;
- identified as galactic objects concentrated in the equatorial plane of the Milky Way ;
- rotation period P between 1.5 ms and a few seconds (8 s) ;
- pulse arrival time extremely stable but increases slowly ($\dot{P} > 0$).

$P - \dot{P}$ diagram for 539 pulsars



Observations: radio emission

Mean profile of PSR 1133+16
and a sample of 100 individual pulses

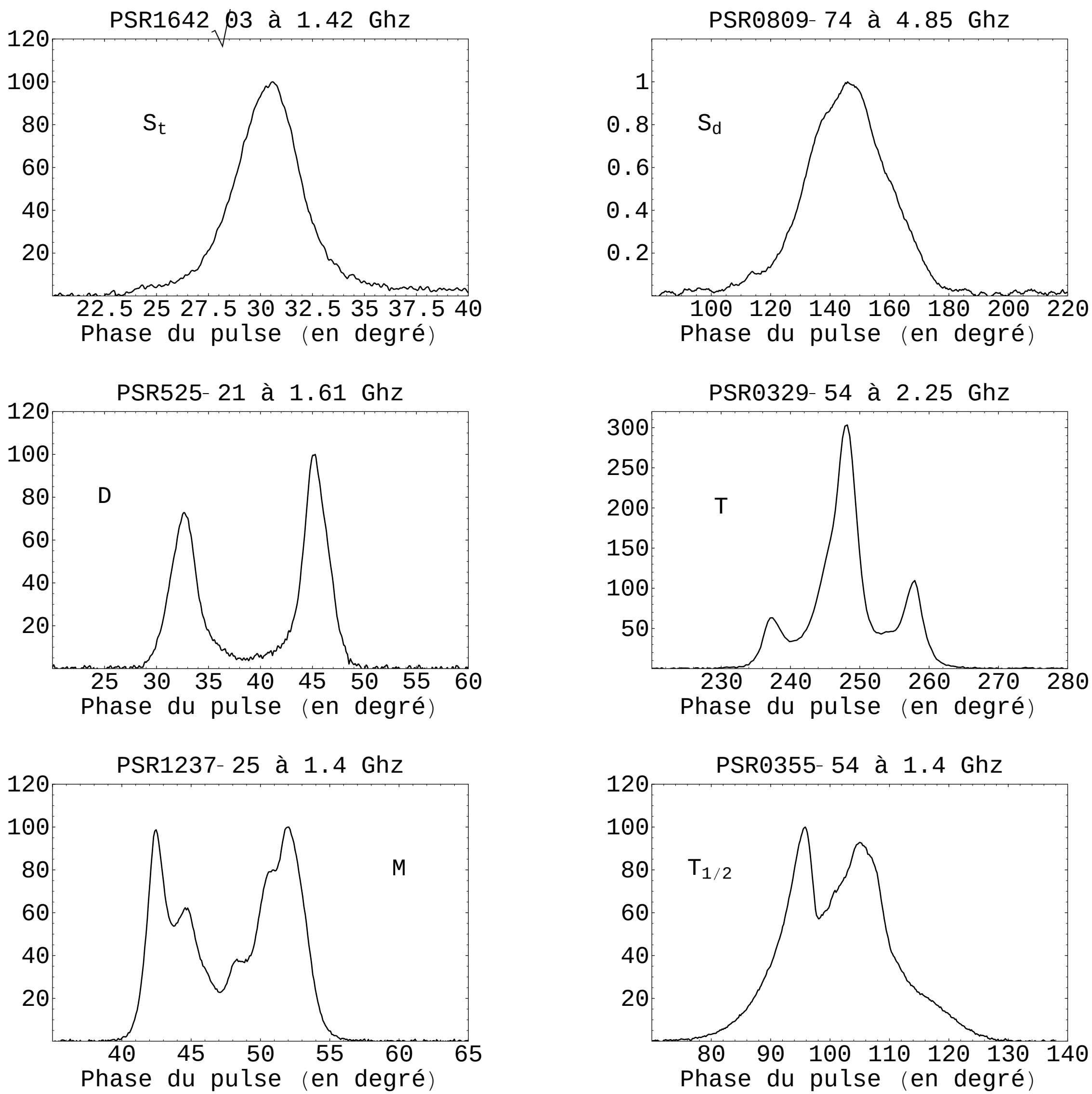


- the structure of the pulse change randomly but the mean profile remains extremely stable ;
- the spectral flux density for radio pulsars decreases like a power law
  $\Rightarrow$ non thermal emission ;
- the radio luminosity is three to five orders of magnitude lower than the total rotational energy losses (mostly released in particle acceleration forming a wind illuminating the supernova remnant by synchrotron radiation) ;
- the brightness temperature for the radio emission is T=10^{23-25} K
  $\Rightarrow$ coherent emission mechanism ;
  - for incoherent emission : intensity $\propto N$;
  - for coherent emission when size of emitting region $L \ll \lambda$: intensity $\propto N^2$.

Radio emission = non thermal coherent radiation mechanism.

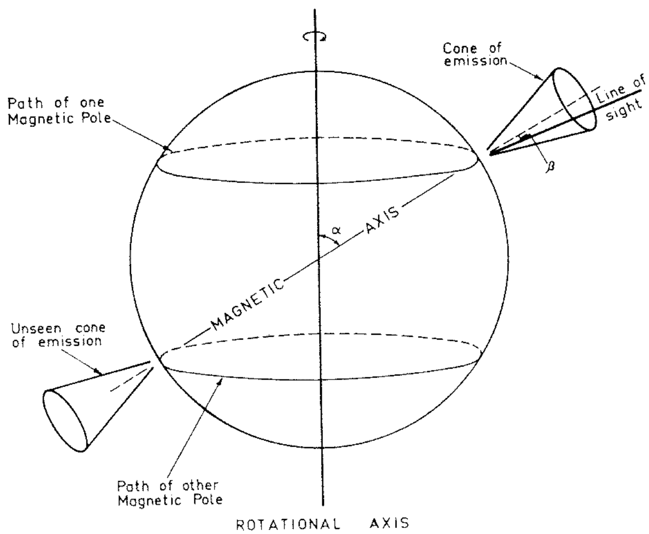
Variety of mean profiles

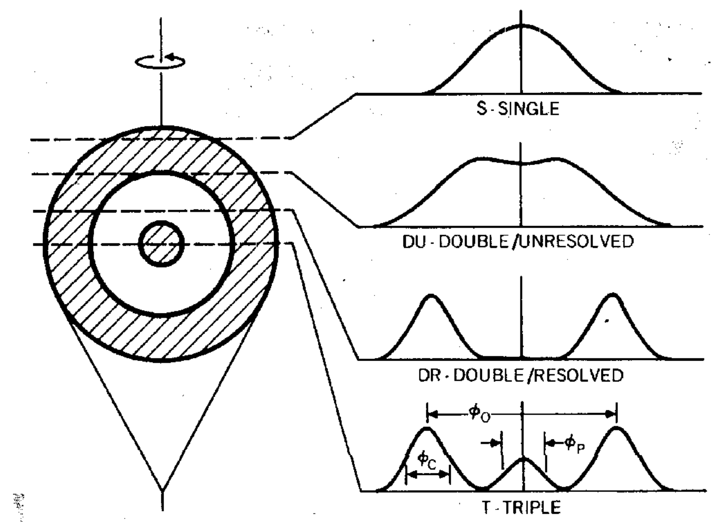
Classification due to Rankin (1983)



Phenomenological model

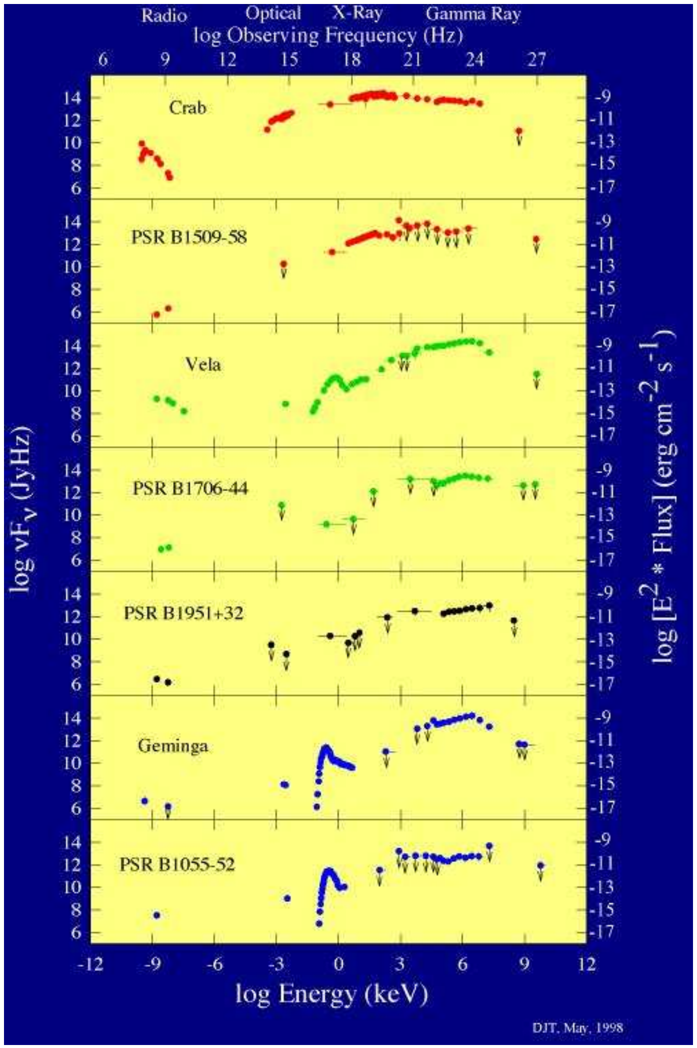
The hollow cone model [Radhakrishnan & Cooke, 1969]





What does the magnetospheric structure look like to explain this model ?

Broad range of emission frequencies



- The radio emission are coherent.
- The visible, X and gamma emission are not necessarily coherent.

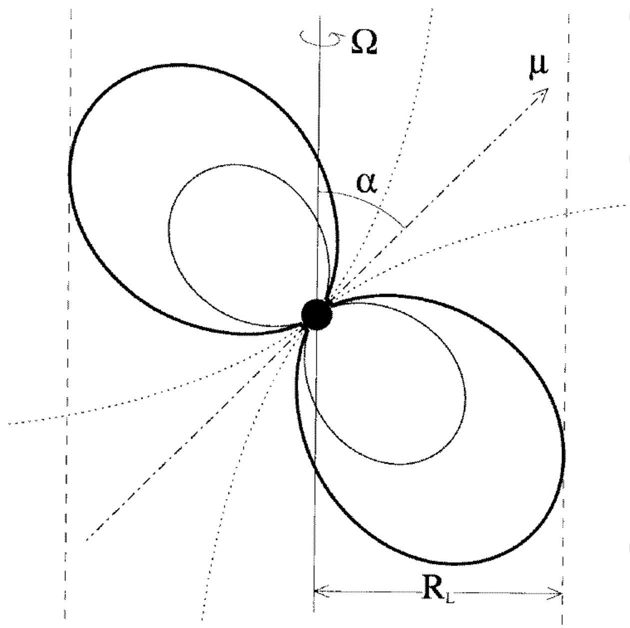
Incoherent emission processes of high energy photons (X, γ)

Emission by ultra-relativistic particles, in a cone of angle $1/\Gamma$ along the magnetic field (relativistic precession).

- synchrotron gyrokinetic radiation of electron spining in the magnetic field. Almost a continuum at high harmonics of ω_c. Critical frequency (max.emission) $\nu_c \approx \frac{3eB}{4\pi mc}\Gamma^2 sin\alpha$ Hz. (E is the energy). Effective when the electrons have a non nul magnetic moment ($sin\alpha \neq 0$, far enough from the star)
- synchrotron curvature radiation of electron moving along curved magnetic field lines. Almost a continuum at high harmonics of ω_c. Critical frequency (max.emission) in PSR's in the Gamma range. $\nu_c = \frac{3c}{4\pi\rho}\Gamma^3$ (ρ is the field line curvature). Very effective close to the star.
- inverse Compton radiation of thermal photons (X, low energy (!)) that get energy from fast electrons (positrons). $\gamma_{LowEnergy} + e^- \rightarrow \gamma_{HighEnergy} + e^-$. The particle gives most of its energy.
  These three processes can produce a huge amount of gamma rays, $E_\gamma > GeV$.

Some useful definitions

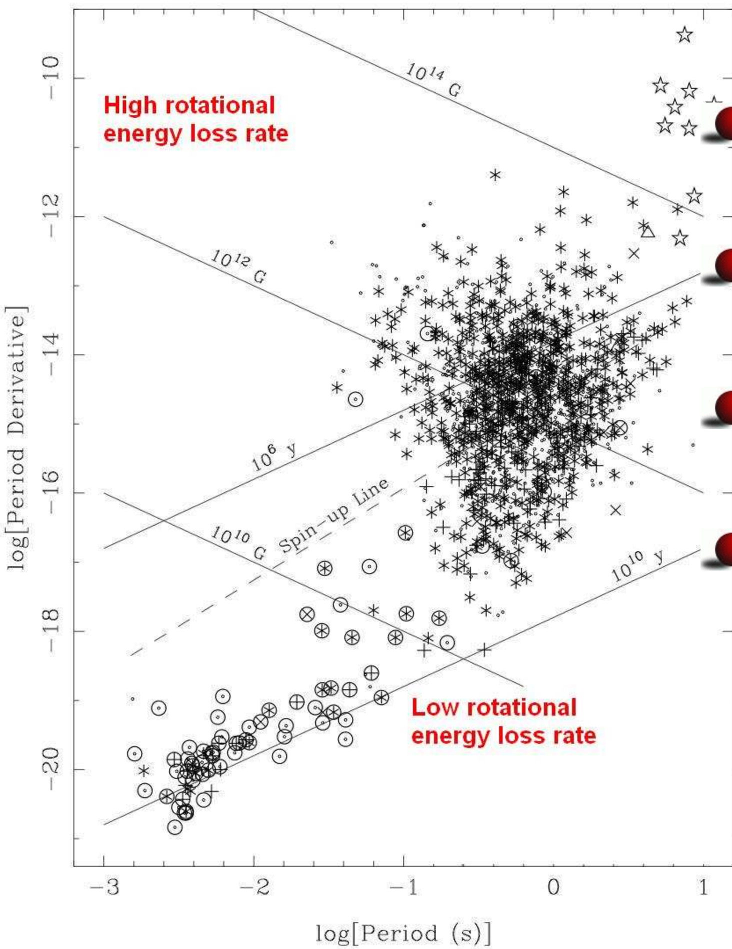
An empty magnetosphere



- Ω_* : rotation axis of the pulsar ;
- μ : magnetic moment ;
- α : angle between the magnetic moment and the rotation axis ;
- the light cylinder : surface where the speed of a particle corotating with the star at a rate Ω_* reaches the speed of light c ; $\Rightarrow$ radius of the light cylinder $R_L = c/\Omega_*$. Large area except for ms pulsars : $R_L/R_* \sim 4.8 \times 10^3 P$.
- Regular increase of the period. Corresponding energy loss $W_{tot} = -I\Omega_*\dot{\Omega}_*$.

Rotation energy loss

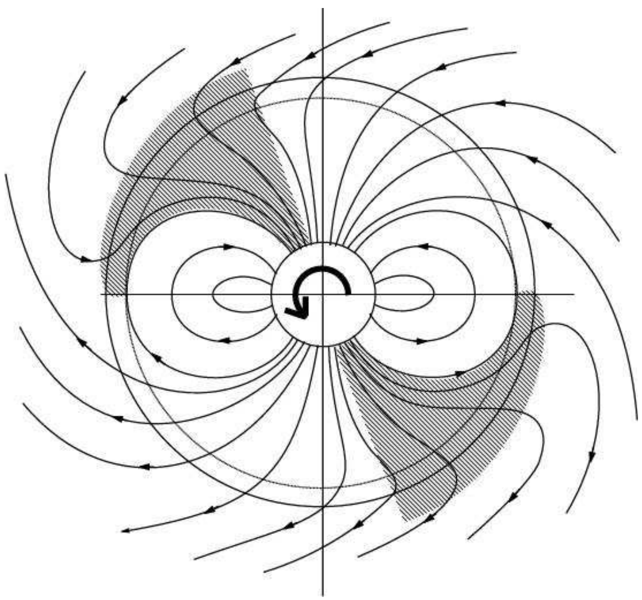
$P - \dot{P}$ diagram. [Manchester 2006]



- Energy losses estimates $W_{tot} = -I \Omega_* \dot{\Omega}_*$, $I_* = 10^{38}\ \mathrm{kg\,m^2}$,
- Standard second pulsar : $P = 1$ s, $\dot{P} = 10^{-15}$, $W_{tot} \sim 10^{24}$ Watt.
- Crab like pulsar :$P \sim 33$ ms, $\dot{P} = 10^{-12}$, $W_{tot} \sim 10^{31}$ Watt.
- Isolated pulsar : the older the slower. Dynamical age: $\tau_{dyn} = P/\dot{P}$.

Energy loss by dipole radiation, an estimate of the magnetic field

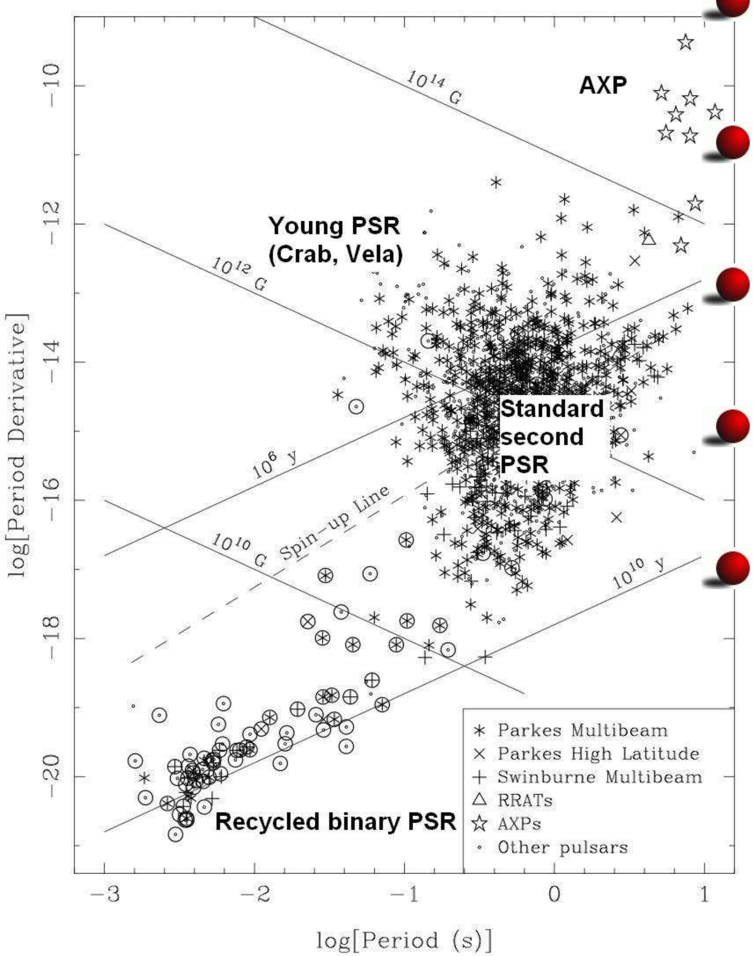
Dipole wave in an empty magnetosphere



- Dipolar magnetic radiation A dipole in rotation into vacuum emits a wave. Can be computed analytically. Energy loss rate $W_{wave} = -\frac{2}{3c^3}\mu_\perp^2\,\Omega_*^4$ where $\mu_\perp$ is the component of the magnetic moment perpendicular to the rotation axis.
- Standard PSR: $P = 1$ s and $\dot{P} = 10^{-15}$ implying $B_* = 10^8\ T$ for s pulsars ;
- Crab PSR: $B_* = 7\times\ 10^8\ T$;
- Fast PSR: $P = 1$ ms and $\dot{P} = 10^{-18}$ implying $B_* = 10^5\ T$ for ms pulsars.

Four famillies of pulsars in the $P - \dot{P}$ diagram

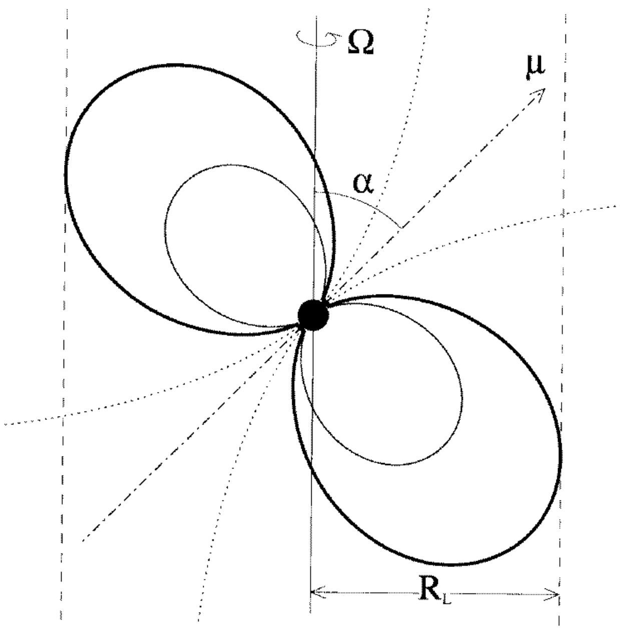
$P - \dot{P}$ diagram. [Manchester 2006]



- Young pulsars are fast with high magnetic field and high losses of rotation.
- Older pulsars are slower, with high (but lower) magnetic field.
- Nonradiating neutron star (slower rotation) do not radiate (beyond death line).
- Recycled binary pulsars : low magnetic field, reactivated through accretion $\longrightarrow$ fast rotation (ms).
- Anomalous X ray Pulsars (AXP) : very high magnetic field (magnetars). Not all magnetars are AXP. (Soft Gamma Repeaters, X and Gamma Ray Bursts are not powered by rotational energy loss.)

But if the magnetosphere is empty...

An empty magnetosphere



- Inside a magnetized conducting sphere in rotation, corotation electric field.
- Outside the sphere (Laplace eq.) the electric field is quadrupolar and vertical. Strong parallel electric field:

$$(\vec{\mathbf{E}} \cdot \vec{\mathbf{B}})_{ext.} = -\Omega B_*^2 R \left(\frac{R}{r}\right)^7 \cos^3 \theta.$$

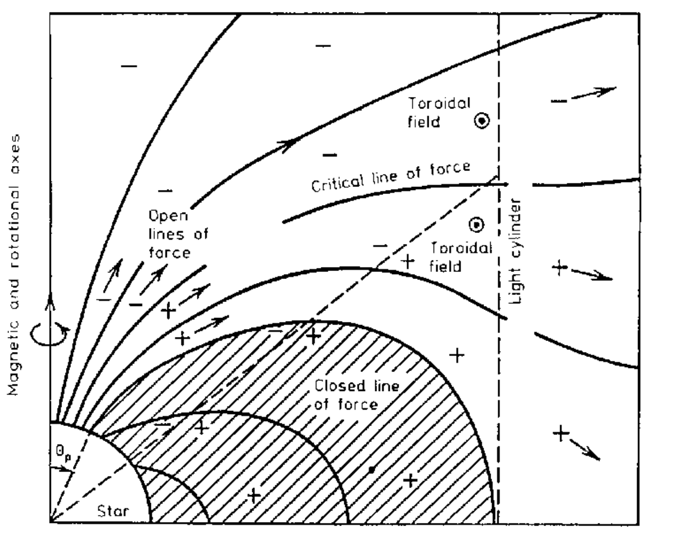
- Electric force much stronger than the gravitation [Goldreich Julian 69]

$$\frac{E_\parallel}{g_\parallel} = 5.2 \times 10^{10} \frac{B_*^2 R^3 \cos^2 \theta}{P(M_*/M_\odot)(m/m_e)}$$

- Electric force can easily overcome the work function to extract electrons... and maybe ions (even iron nuclei) from the crust [Flowers, Müller, Neuhauser, Jones]

Magnetosphere with a plasma modelized as a unipolar inductor.

The magnetosphere of (Goldreich-Julian, 1969)

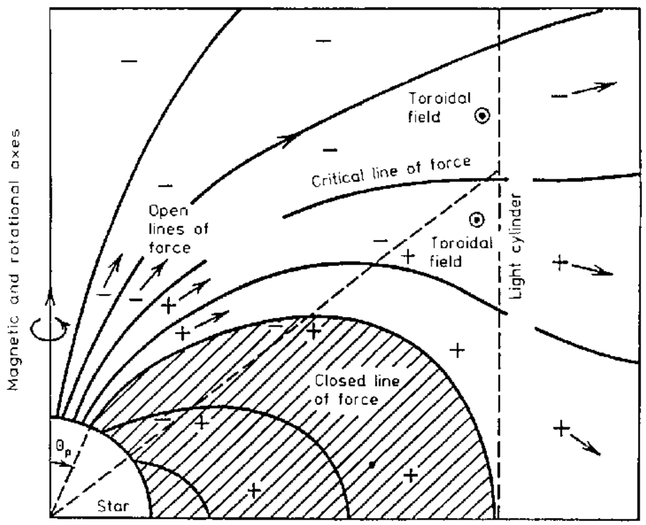


Assumptions :

- an aligned rotator ($\vec{\Omega}_* \parallel \vec{\mu}$) ;
- a closed magnetosphere entirely filled with the corotating plasma up to the light cylinder ;
- Cold plasma in electrostatic equilibrium : $\vec{E} + \vec{v} \wedge \vec{B} = 0$;
- particles follow a electric drift motion in the $\vec{E} \wedge \vec{B}$ direction ;

Magnetosphere with a plasma modelized as a unipolar inductor.

The magnetosphere of
(Goldreich-Julian, 1969)

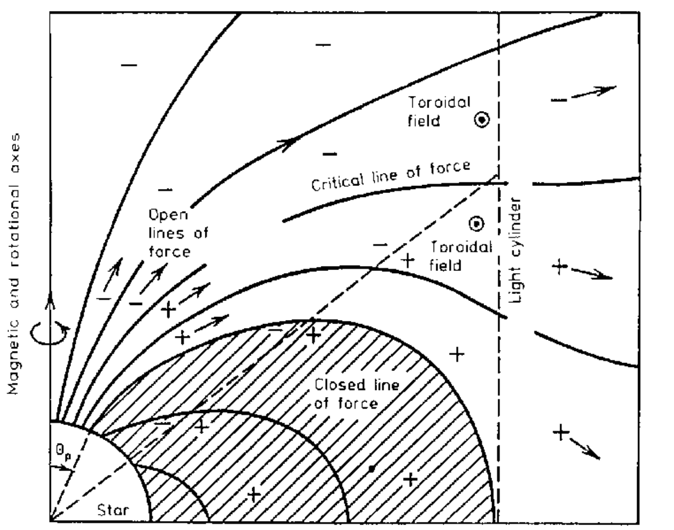


The corotating region is shaded

- A corotating plasma $\vec{E}_{corot.} + (\vec{\Omega}_* \times \vec{r}) \times \vec{B} = 0$
- At the star surface, $E \sim \Omega_* R B_*/c \sim 10^8 - 10^{10}$ V.m^{-1}.
- Goldreich-Julian charge density derived from $\vec{E}_{corot.}$, $n_{GJ} = -2\epsilon_0 \vec{\Omega}_* \cdot \vec{B}$. Near the crust $n_{GJ} \sim 10^{11} - 10^{12}$ cm^{-3} . (Near Jupiter $n_{GJ} \sim 10^{-5}$ cm^{-3} .)
- The null surface: region where the charge density vanishes ($\vec{\Omega}_* \cdot \vec{B} = 0$) ;
- Iso-potential corotating field lines, $E_{corot.} \cdot \vec{B} = 0$
- The Goldreich-Julian current density perturbs the magnetic field. Large near the light cylinder.

The polar cap model

The magnetosphere
(Goldreich-Julian, 1969)

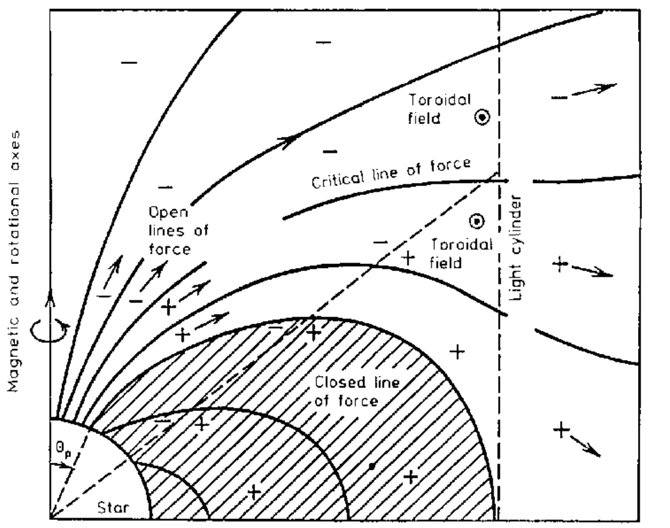


Far from the star, the polar gap fills the whole space.

- The corotation is only possible in the inner region where the field lines do not cross the light cylinder (no supraluminic motion).
- The other field lines define the polar cap where the electric drift motion hypothesis is broken, with parallel electric fields.
- When $P = 1$s, $\Delta\theta \sim 1^o$, 200 m. For a ms pulsar, $\Delta\theta \sim 20^o$.

Differences with the solar and planetary plasmas

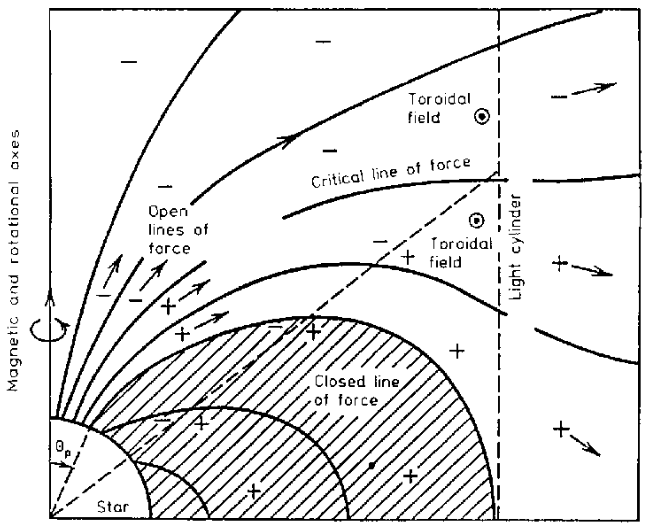
The magnetosphere (Goldreich-Julian, 1969)



- Near the star, $\hbar\omega_{ce} > m_e c^2$, the perpendicular energy states in B of the electrons are quantified... at the fundamental level : null pitch-angle. No mirror effect.
- If not quantified, gyrosynchrotron radiation efficiently dissipate any kinetic perpendicular energy. Null pitch angle. No mirror efect.
- Because of rotation charge density (or other), the plasma is not necessarily neutral.
- The particle are highly relativistic.
- Close to the star, the metrics is not euclidian (General Relativity).
- Quantum electrodynamics : possibility of $e^- e^+$ pair creations.

Acceleration in the polar cap

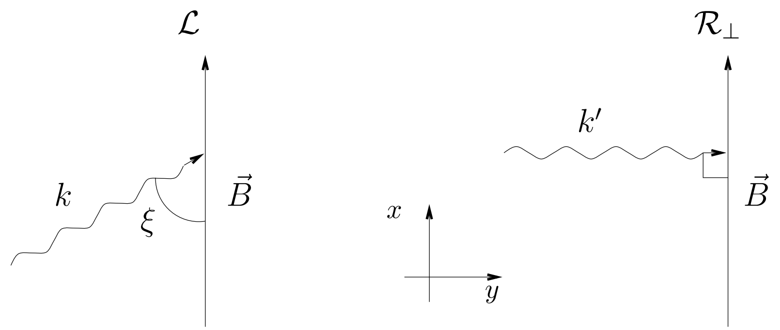
The magnetosphere
(Goldreich-Julian, 1969)



- Open field lines : potential difference from star surface $\Phi_{corot.}(R_*, \theta)$ to infinity $\Phi = 0$. Conditions for setting a very strong double layer, since over the polar cap, $\Delta\Phi(r = R) \sim 10^{13} - 10^{15}$ V.
- Accelerate electrons up to $\Gamma \sim 10^5 - 10^6$ over an altitude of 100m above the crust. [Bonazzola, personal communication.]
- But such fast particles in a strong magnetic field radiate gamma rays.

Filling the magnetsophere: Pair creation e^+e^- (1)

- a quantum electrodynamics process in a strong magnetic field of the order of critical magnetic field $B_c \approx 4.4 \cdot 10^9$ T : $\gamma + B \rightarrow e^+ + e^-$



In the frame $\mathcal{R}_\perp$, the threshhold energy is given by $k' = k\,\sin\xi \geq 2\,m_e\,c^2$. ($E_\gamma = k\,m_e\,c^2$)

- for a given photon energy, the efficiency increases with the magnetic field intensity $\Rightarrow$ occurs solely in the innermost regions of the magnetosphere ;
- the photons are produced by :
  - * curvature and synchrotron radiation $\Rightarrow$ constraint on the maximum energy reached by the charges, $\Gamma < 10^7$;
  - * inverse Compton diffusion ;

Filling the magnetsophere: Pair creation e^+e^- (2)

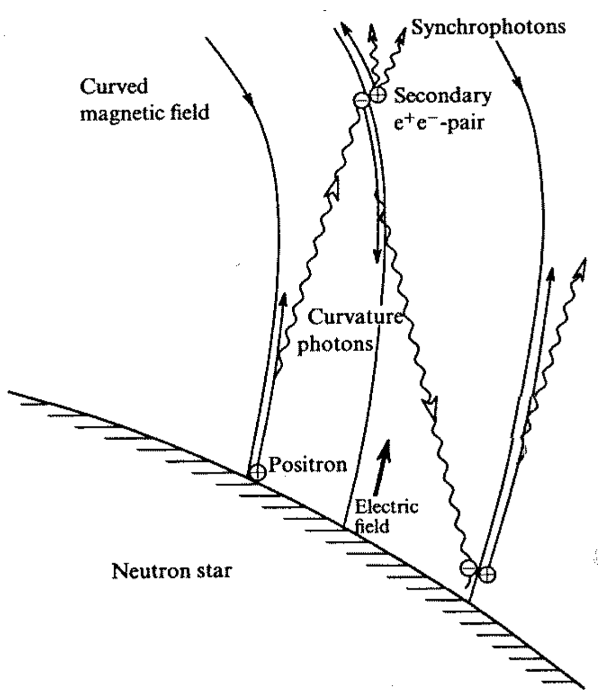
- photon-photon interaction via the process :

$$\gamma + \gamma \rightarrow e^+ + e^-$$

- interaction between a gamma photon emanating from the outer gaps and a thermal photon created by the black body radiation from the hot stellar crust ;

Charged wind

Pair creation cascades (Sturrock 1970, Ruderman & Sutherland 1975)

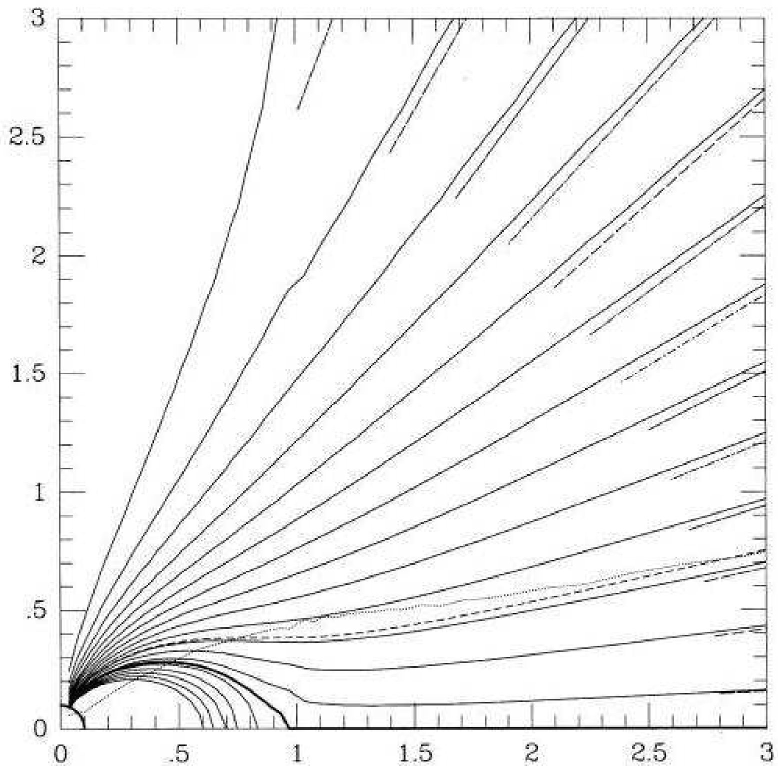


- the corotation impossible outside the light cylinder R_L ;
- a charged wind emanating from the polar caps
- the charged particles (e^+e^-) are produced by $\gamma + B \rightarrow e^+ + e^-$ in the polar caps.
- the open field lines sustain a wind made of particles of both signs $\Rightarrow$ increase or decrease of the total charge of the system (star+magnetosphere) ;

$\Rightarrow$ problem of the current closure.

Solution for the axisymmetric rotator

(Contopoulos et al.,1999)



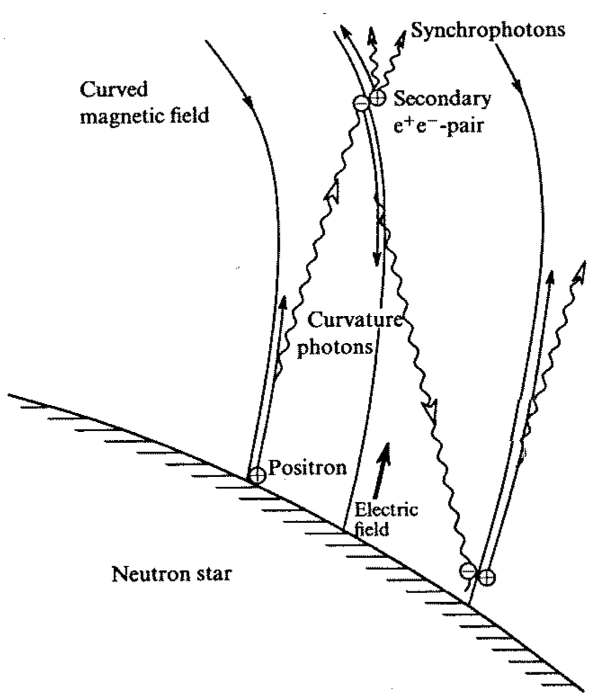
The previous models do not solve the problem of the closure of the electric circuit :

- Solved by [Contopoulos et al 99], by following the last open magnetic field line : current sheet ;
- by violation of the electric drift approximation. Particles follow the surface of the light cylinder (Beskin, Mestel).
- For the first time, [Contopoulos et al 99] find a self consistent solution that connect the polar cap, the region beyond the light cylinder, and take the current closure into account.
- (Is the nature of the return current carriers clear ? Incomming electrons, outflowing positrons, ions ?)

The polar gap model is not compatible with the gamma emissions

Aim: to explain the high energy component of the pulsar's spectrum (gamma emission)

Pair creation cascades
(Sturrock 1970, Ruderman & Sutherland 1975)



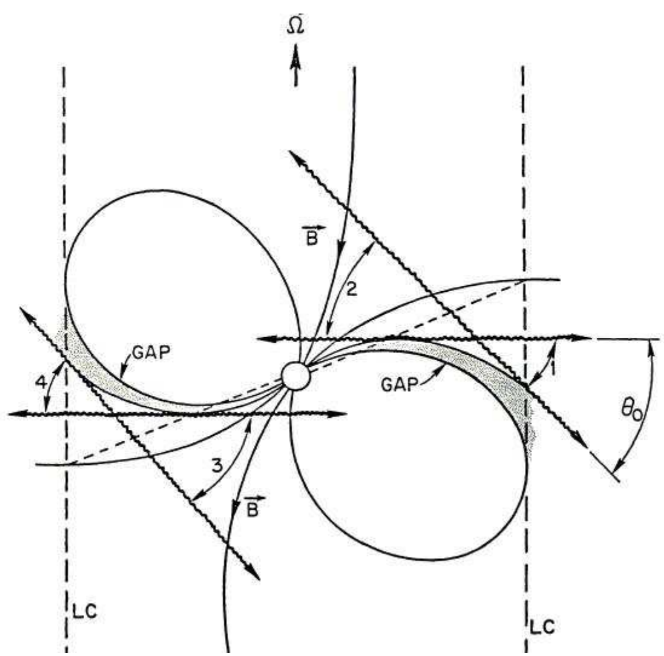
Assumptions :

- The particles accelerated in the polar cap radiate gamma rays.
- In the case of young pulsars (strong B) the gamma photons are absorbed to emit pairs.
- The gamma rays emitted in the polar cap cannot be observed;
- The accelerated particles that emit the observed gamma ray are produced in more distant areas.

Outer gap model

Aim: to explain the high energy component of the pulsar's spectrum (gamma emission)

(Cheng, Ho & Ruderman 1986)



Assumptions :

- the outer gaps are located between the light cylinder and the null surface ;
- the photon disintegration is impossible because B too weak ;
- the pair cascade initiated by photon-photon interaction in the outer gaps, $\gamma + \gamma \rightarrow e^+ + e^-$;
- the curvature photons emitted tangentially to the local magnetic field lines.

An alternative model:
the two pole caustic = slot gap from the light cylinder down to the stellar surface (Dyks & Rudak 2003).

Conciliating the polar cap, the outer gap, and radiation spectra

The ingredients in Hirotani's model

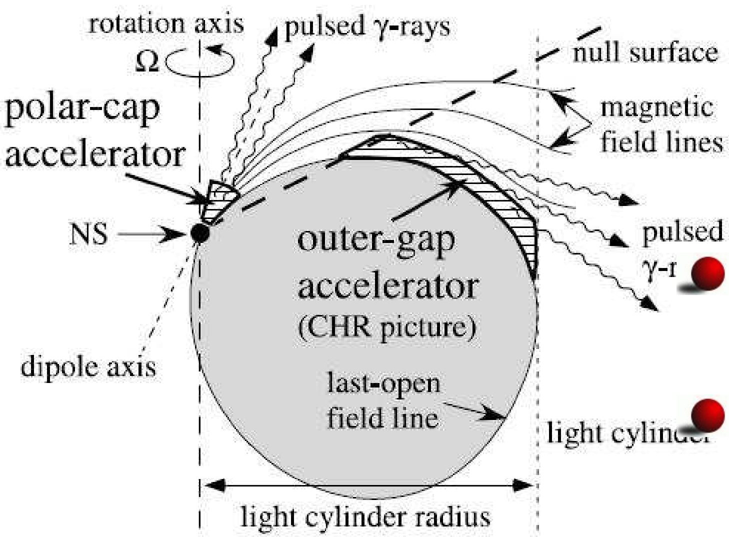
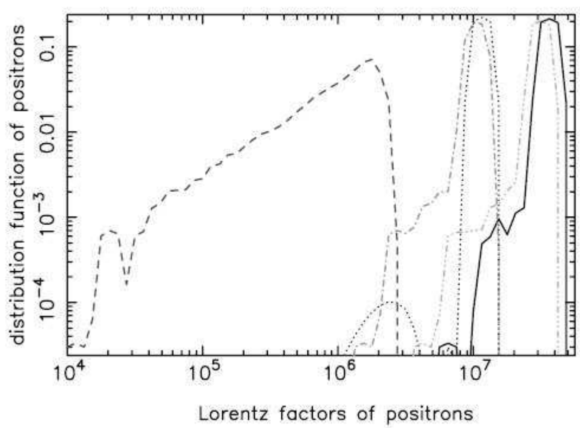


FIG. 1.—Schematic figure (side view) of the two representative accelerator models. The small filled circle represents the neutron star.

- Include the polar cap, the outer gap, ,the light cylinder, the breaking of the electric drift motion, the incoherent radiation and pair production processes, the RG space-time. (Does include the surface of the crust but with a uniform potential.)
- The latitudinal extend of the outer gap is given as a free parameter.
- The acceleration occurs mainly in the outer gap.

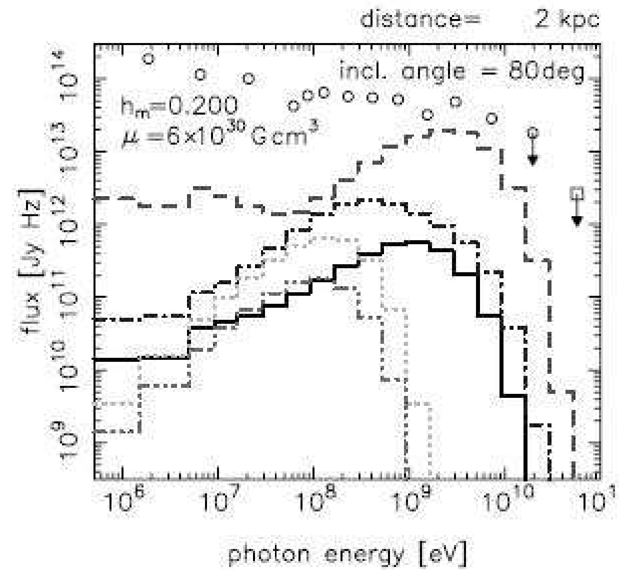
Conciliating the polar cap, the outer gap, and radiation spectra

Particle acceleration [Hirotani 06]



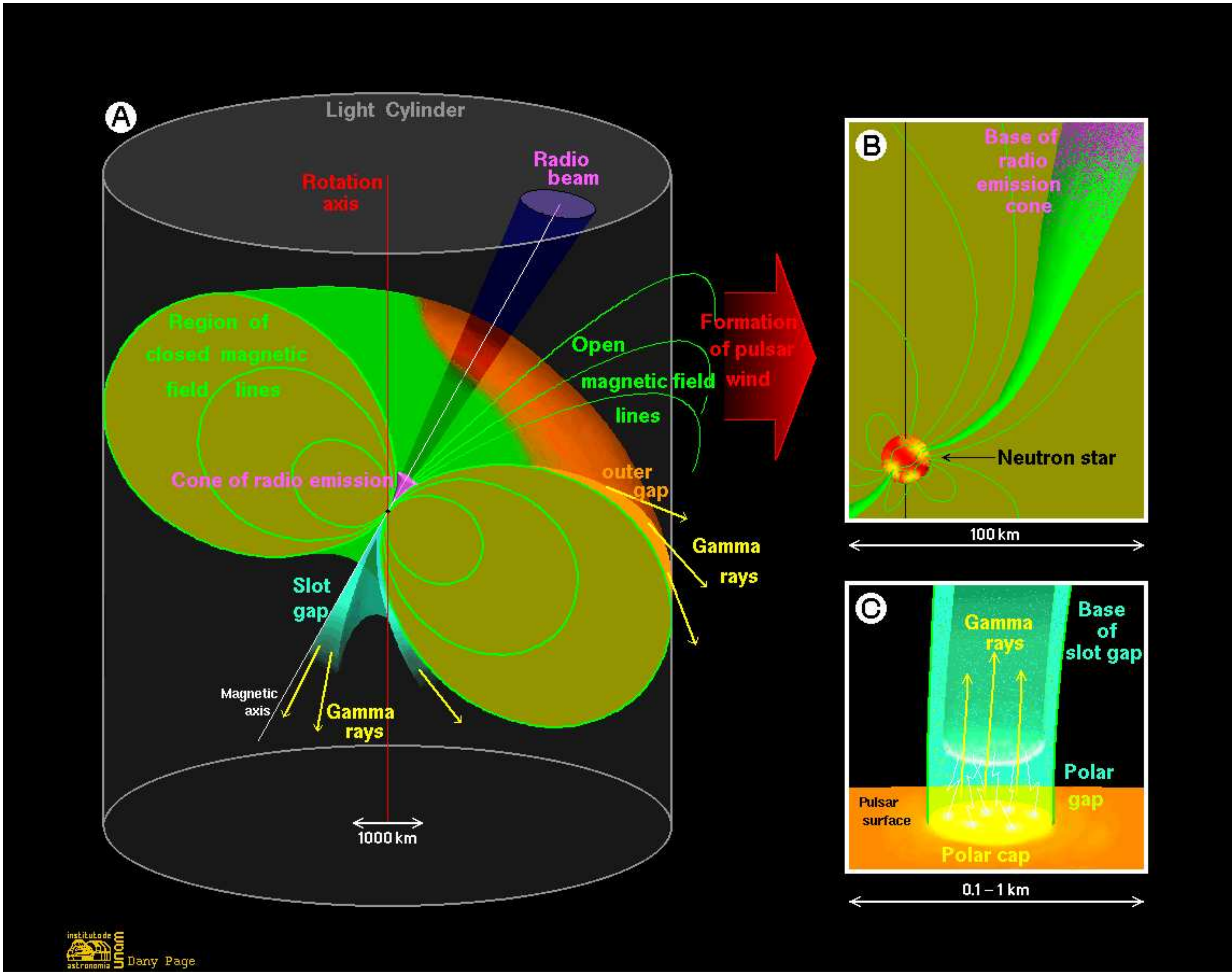
Positron and electron acceleration up to high energies ($\Gamma > 10^7$). (Curves for various distances along field line. Most energetic upward, beyond the light cylinder.)

High energy photon spectrum [Hirotani 06]



The gamma rays emitted in the outer gap reproduce reasonably well the observed spectra of the Crab pulsar. (Ad hoc outer gap thickness, curves for various magnetic inclination angle α.)

Summary of the “standard” model



Electrospheric model

Aim

Construction of a self-consistent electrosphere for a charged and aligned pulsar.

Assumptions :

- the neutron star = perfect spherical conductor of radius R_*, generating a dipolar magnetic field of strength B_* and in solid body rotation with speed Ω_* ;
- an aligned rotator, i.e., magnetic moment and spin axis are parallel ;
- particles located well within the light cylinder ;
- charges extracted freely from the stellar crust whatever their nature ;
- magnetic field induced by the electrospheric currents are neglected $\Rightarrow$ constant and dipolar ;
- any force other that electromagnetic are neglected (even the gravitational attraction !!) ;
- the electric drift approximation ;
- the spacetime curvature neglected (frame dragging effect).

Iterative scheme

Qualitative picture

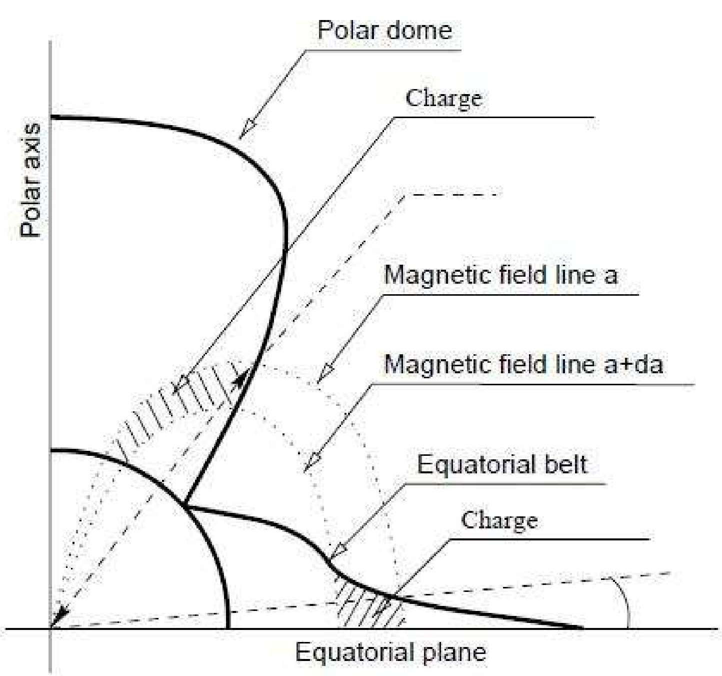


Fig. 1. Schematic representation of the geometrical shape of the electrosphere, illustrating the definition of the parameters $\alpha(a)$ and $R_\gamma(a)$ that describe its boundaries depending on the magnetic line a.

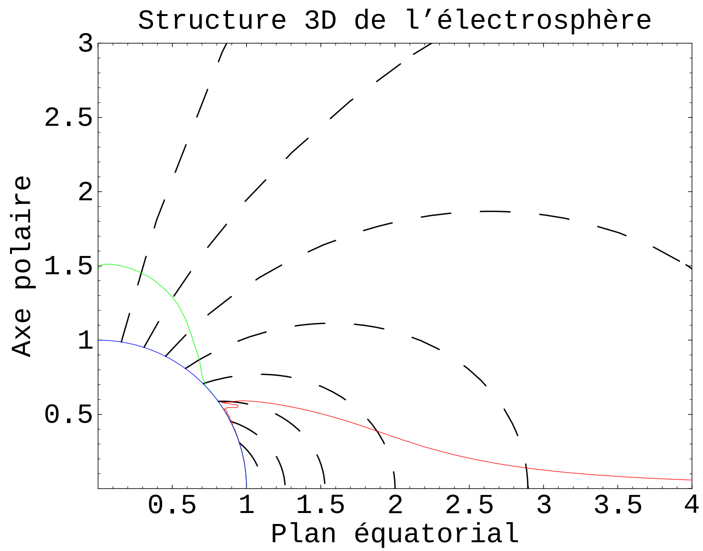
Total charge Q_{tot}
= only parameter of the model

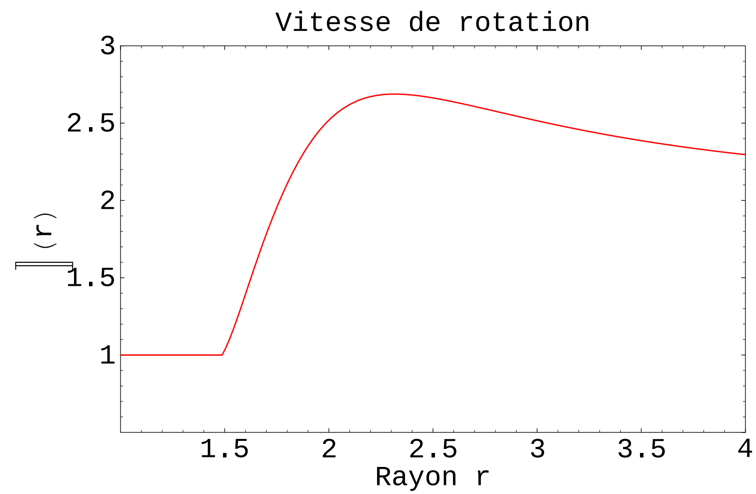
Algorithm :

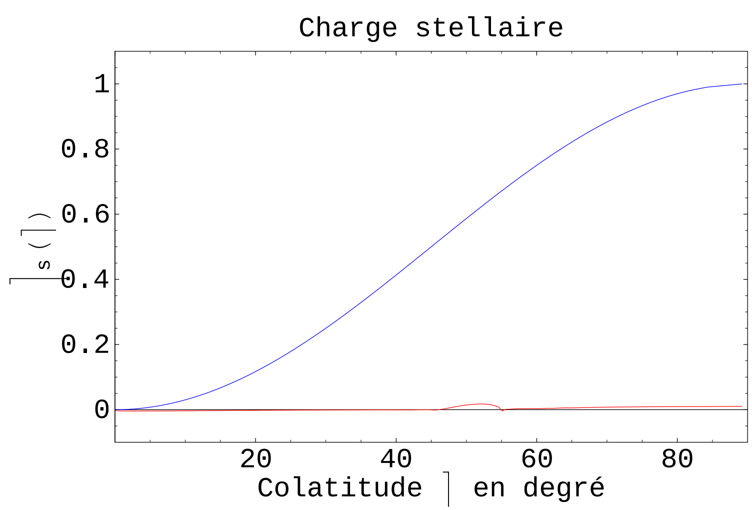
1. Transfer a fraction p of the stellar surface charge ;
2. Evaluate the total electric potential ϕ (star+electrosphere)
3. Find the differential rotation speed Ω din the non corotating region ;
4. Deduce the associated differential charge density $\rho_{\neq}$;
5. Find the new volume occupied by the plasma ;
6. Return to step 2 until self-consistency is achieved between ϕ, Ω et $\rho_{\neq}$;
7. Return to step 1 until total vanishing of the stellar charge.

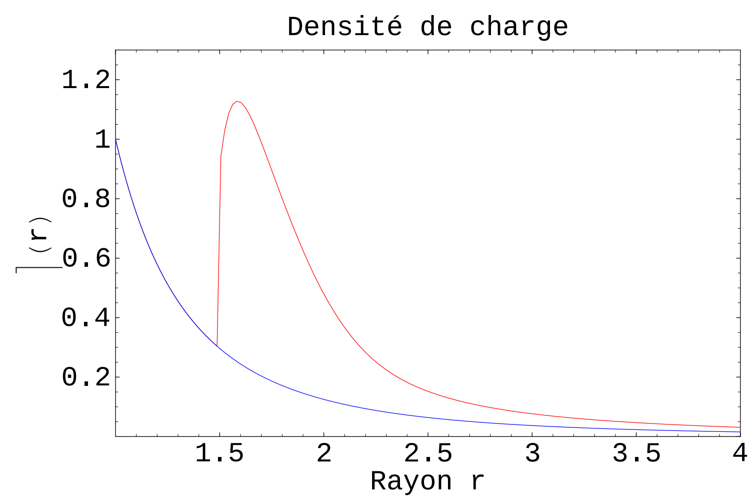
Results: electrospheric structure

(Pétri, Heyvaerts & Bonazzola, A&A 2002a)









Results: electrospheric structure

Main features :

- electrosphere of both sign ;
- is finite in extent for $Q_{tot} \leq 3\,Q_c$. Moreover, if $Q_{tot} \ll 3\,Q_c$, plasma is confined well inside the light cylinder ;
- has large gaps appear between the equatorial belt and the polar domes ;
- there is no electric current circulation in the gaps ;
- a differential rotation of the disk, overrotation
  $\Rightarrow$ induce a shearing between magnetic surfaces responsible for the growing of an instability ;
- the same qualitative conclusions whatever apply the total charge Q_{tot}.

The electromagnetic field acts as a Penning trap, confinement of the non-neutral plasma:

- in the radial direction by the magnetic field :
- in the “axial” direction by the electric field.