Magnetosphères lointaines mais observables

Fabrice Mottez

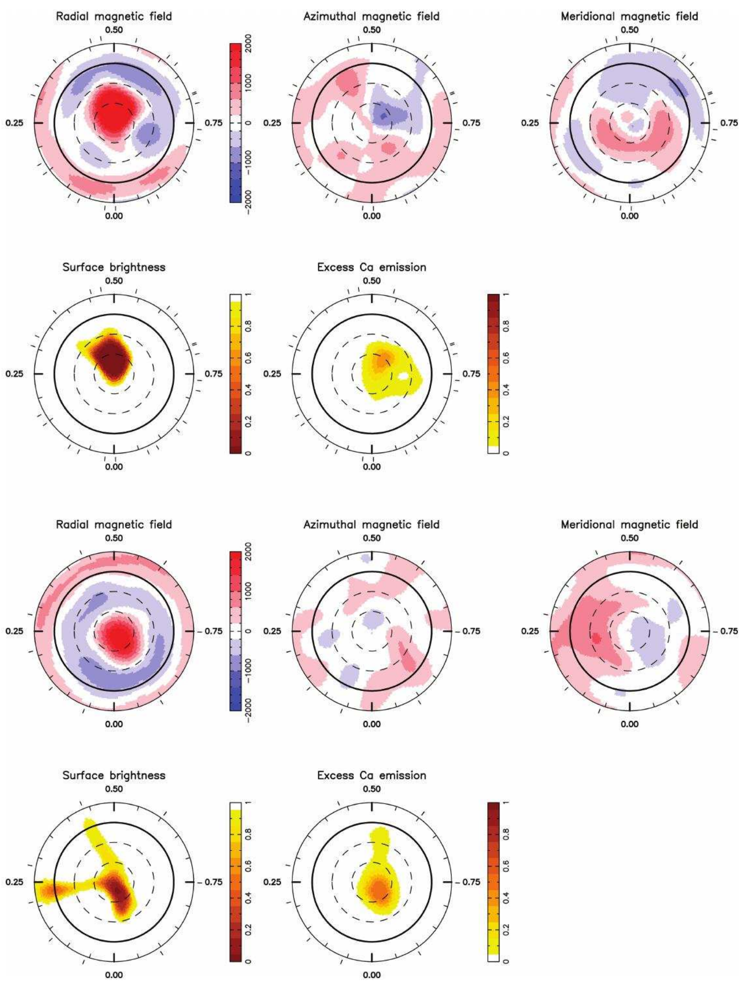
Laboratoire Univers et THéories (LUTH) - Obs. Paris-Meudon - CNRS - Univ. Paris Diderot

Magnétosphères

Uranie cache maladroitement son dernier prototype d'étoile à neutrons à sa copine Calliope. [S. Vouet 1634]

- Planètes magnétisées en rotation (Jupiter, Saturne, Terre...)
- Planètes magnétisées dans un vent derrière une onde de choc (Mercure, Terre...)
- Planètes dans un vent, non protégées par une onde de choc (Io, Ganymède)
- Etoiles ? (magnétisées, en rotation)

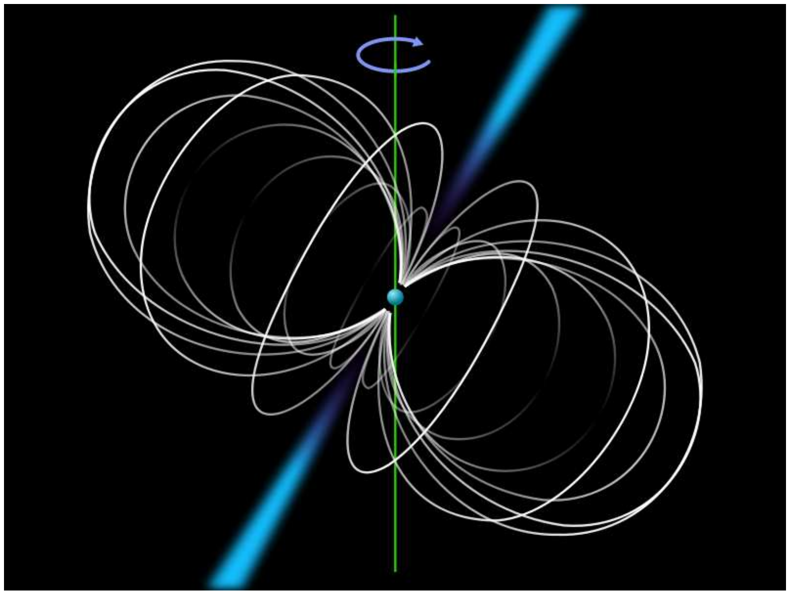
Etoiles



Etoile V2190 Oph, à 4 ans d'écart.
[Donati + 2011]

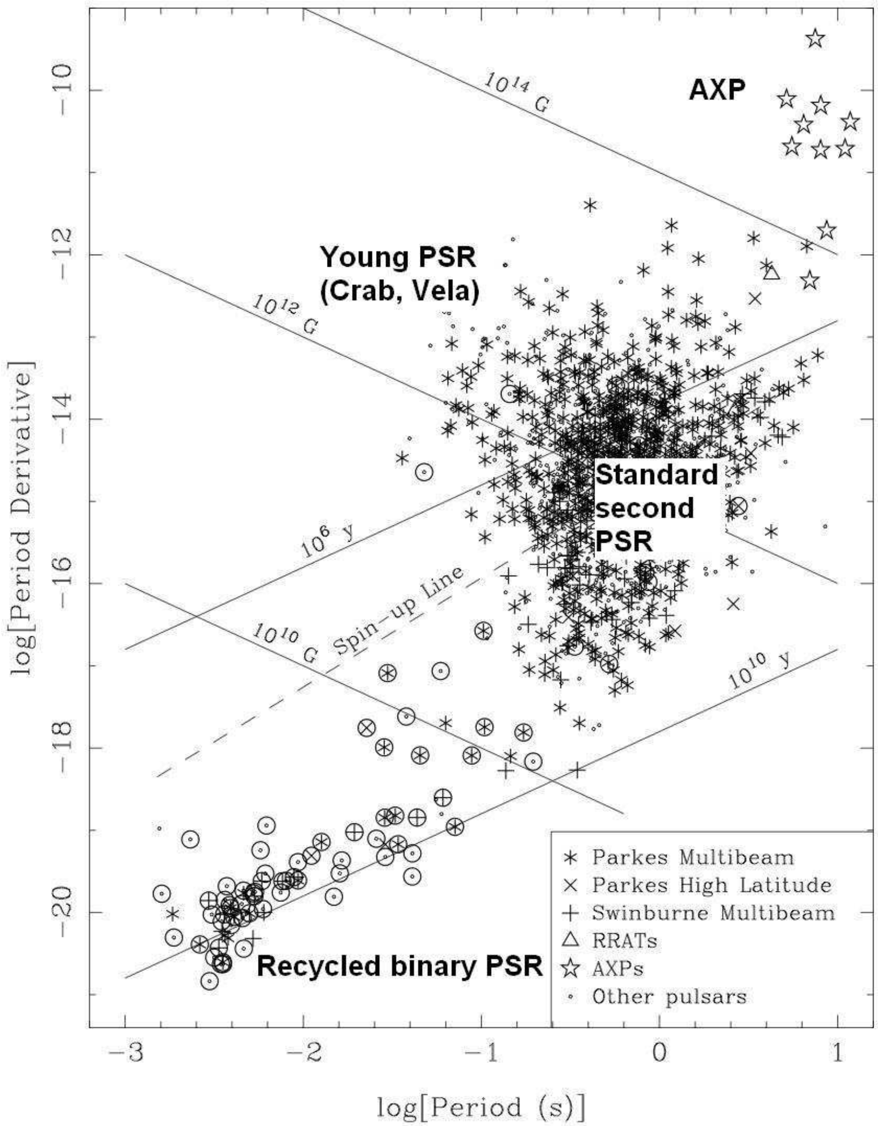
- Etoiles ? (magnétisées, en rotation)
- Soleil : dynamique conduite par le déplacement en surface de l'étoile des tubes de flux.
- Echelles rapides : émergence tubes de flux / convection du plasma interne.
- Echelles lentes : cycle (11 ans pour le Soleil) de la dynamo.
- Soleil : couronne $\neq$ magnétosphère.
- Idem étoiles vues par ESPADON.
- Magnétosphères : étoiles où $\vec{B}$ est figé. Pas de convection, pas de dynamo.
- Magnétosphère de naines blanches, et d'étoiles à neutrons.

Etoiles à neutrons : The theoretical problem is simple



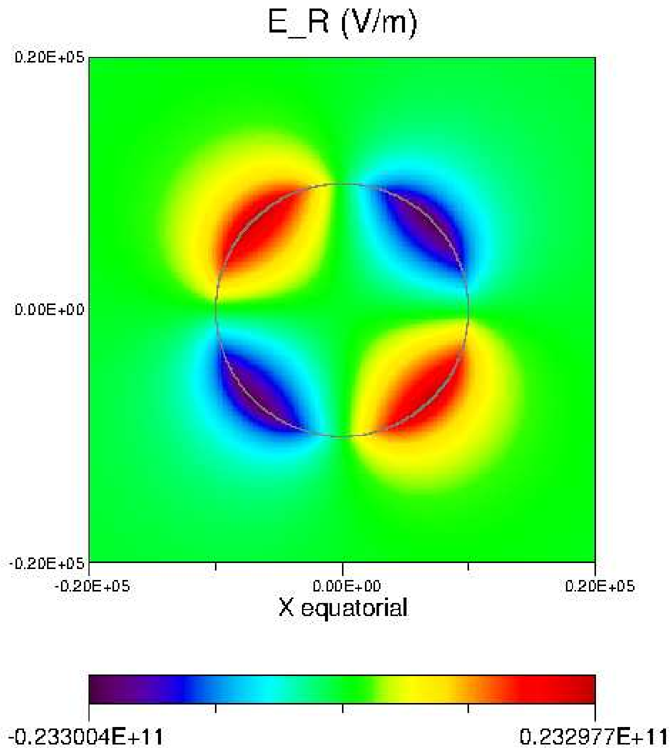
- A conducting sphere, $R \sim$ 10 km.
- in fast rotation, $P = 1$ ms–10 s.
- A high (dipole) stellar magnetic field $B_* = 10^5$ to 10^8 T, and even 10^{11} T for magnetars
- Magnetic axis inclination i over the rotation axis.
- The star is an infinite supply of charged particles. The potential to extract them is negligible (like with a diode anode).
- Even simpler : When $i = 0$: *aligned pulsar*, axisymmetric problem.

We know the input of energy into the pulsar!



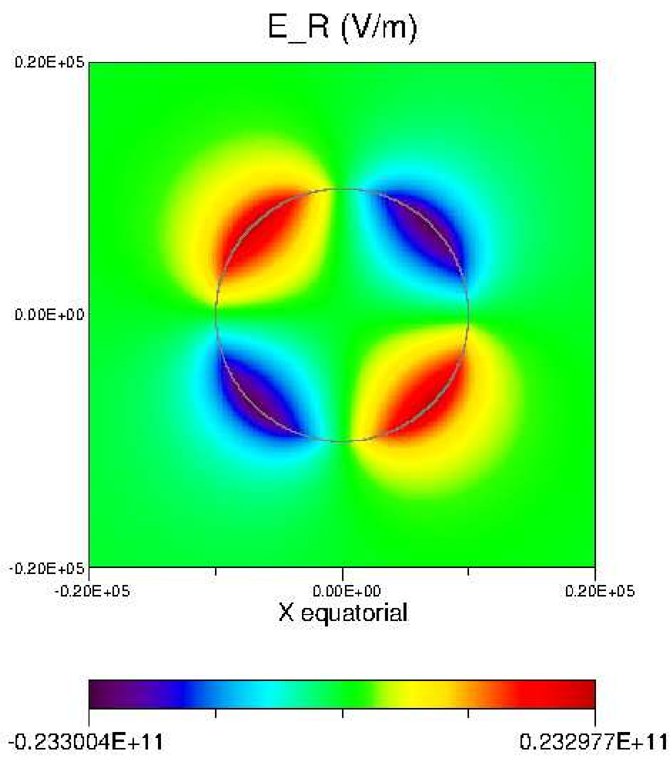
- Huge statistics on rotational properties.
- Radio astronomy:
  periods P and time derivatives $\dot{P}$, $\ddot{P}$...
- Theory of neutron stars:
  Radii $R_* \sim 10$ km
  Mass $M_* \sim 1.5\ M_\odot$
  Moment of inertia $M_I \sim 10^{38}$ kg.m^2.
- Loss rate of rotational energy :
  $\dot{E}_{rot} = -M_I \Omega_* \dot{\Omega}_* = 4\pi^2 M_I \dot{P} / P^3$.

Feeding the pulsar magnetosphere with *primary* electrons



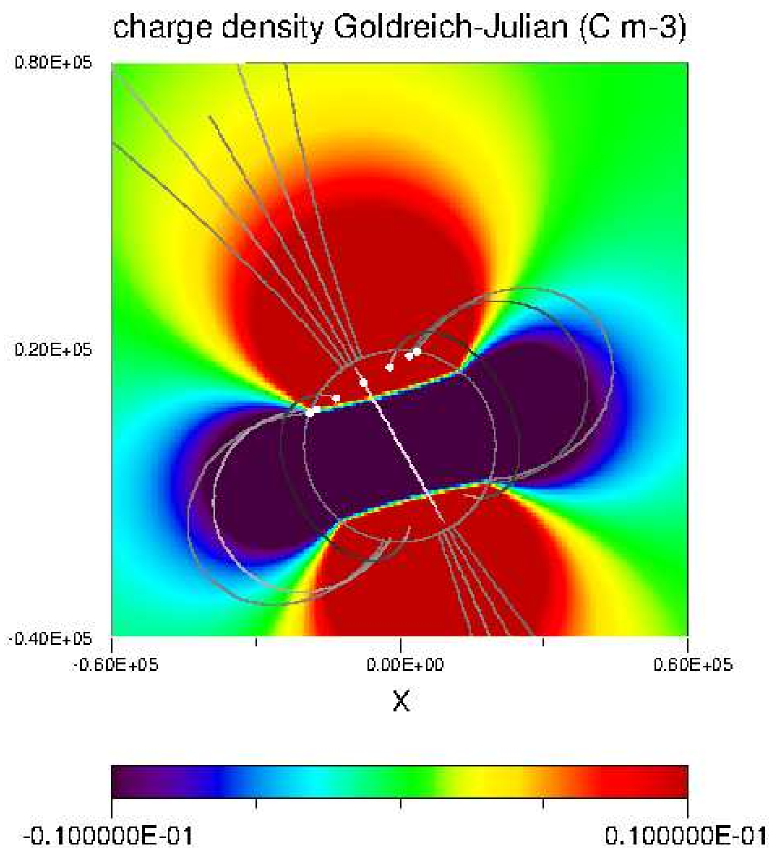
- On the neutron star surface, $E_r = E_{vertical} \neq 0$.
- Electric force $\sim 10^6 \times$ gravitational force and $>>$ surface cohesion forces.
- Therefore the star is surrounded by a plasma forming a magnetosphere.

Rayonnement synchrotron



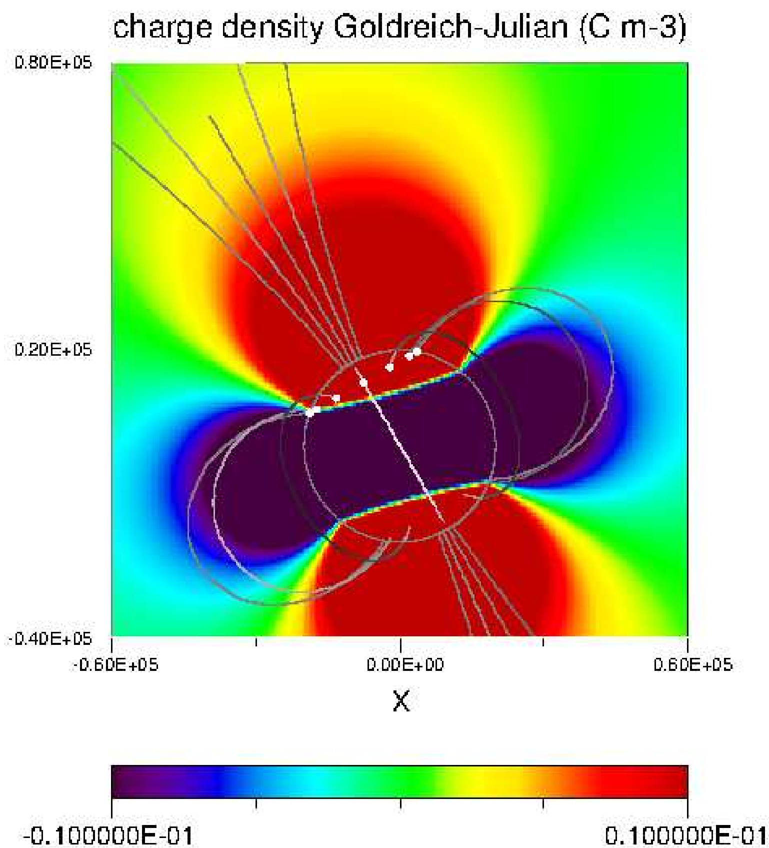
- Les électrons, violemment accélérés, sont relativistes, $\Gamma_{Lorentz} \sim 10^5$.
- Rayonnement synchrotron : puissance $\sim \Gamma^2_{Lorentz} B^2/m^2$.
- Un electron perd toute la vitesse cyclotron $v_\perp$ en 10^{-17} seconde.
- Pas d'effet miroir, pas de dérive de courbure ou de gradient.

Plasma in corotation



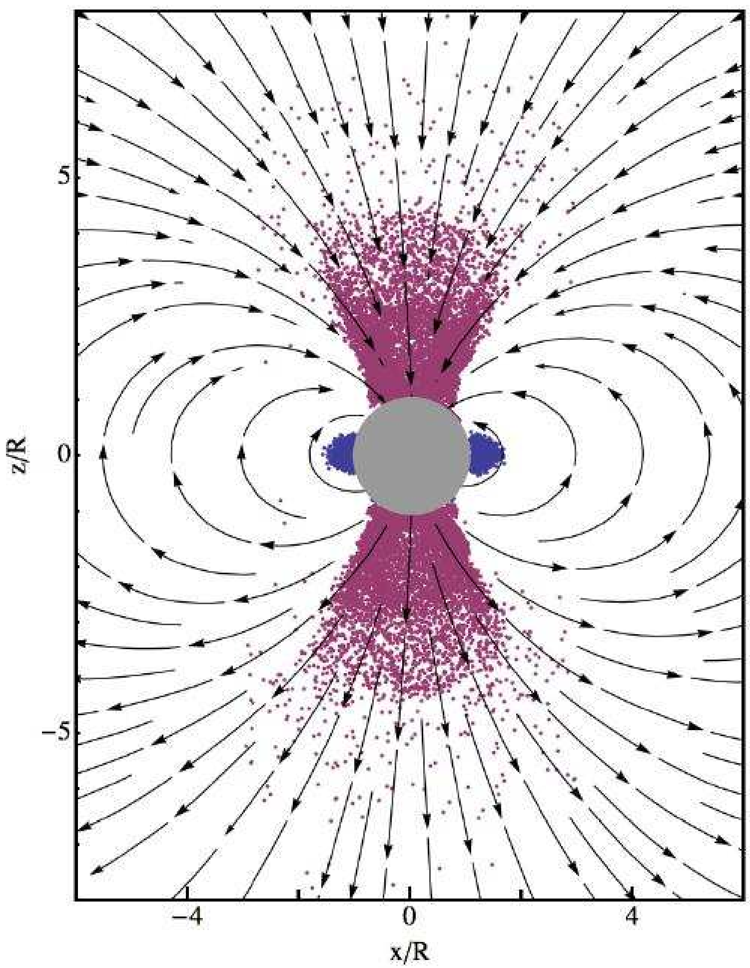
- Pulse regularity: continuous emission.
- Search for a stationary solution in the Ω_* rotating frame.
- Then, in the rotating frame, $\vec{E}_{RF}$ derives from a potential.
- Simplest assumption: $E_{RF} = 0$. Then, in observer's frame $\vec{E}_{GJ} = (\vec{r} \times \vec{\Omega}_*) \times \vec{B}(\vec{r})$. [Goldreich-Julian 1969]
- They are associated to the Goldreich-Julian charge and current densities $\rho_{GJ} = \epsilon_0 \nabla \cdot \vec{E}_{GJ}$ and $J_{GJ} = c\rho_{GJ}$.
- Le plasma n'est pas neutre !

Plasma in corotation



- Nevertheless, $E_{RF} = 0$ is only a simplifying assumption.
- What happen when $\vec{r} \times \vec{\Omega}_* \sim c$? This defines the light cylinder radius $R_{LC} = c/\Omega_*$.
- This assumption provides no way of computing the real shape of the electromagnetic field.
- Region of closed field lines not farther than R_{LC}: no problem with co-rotation.
- Polar caps. Open field lines. Cannot co-rotate all along the field lines.
- Implies a parallel electric field $\neq E_{GJ}$ above the polar caps.

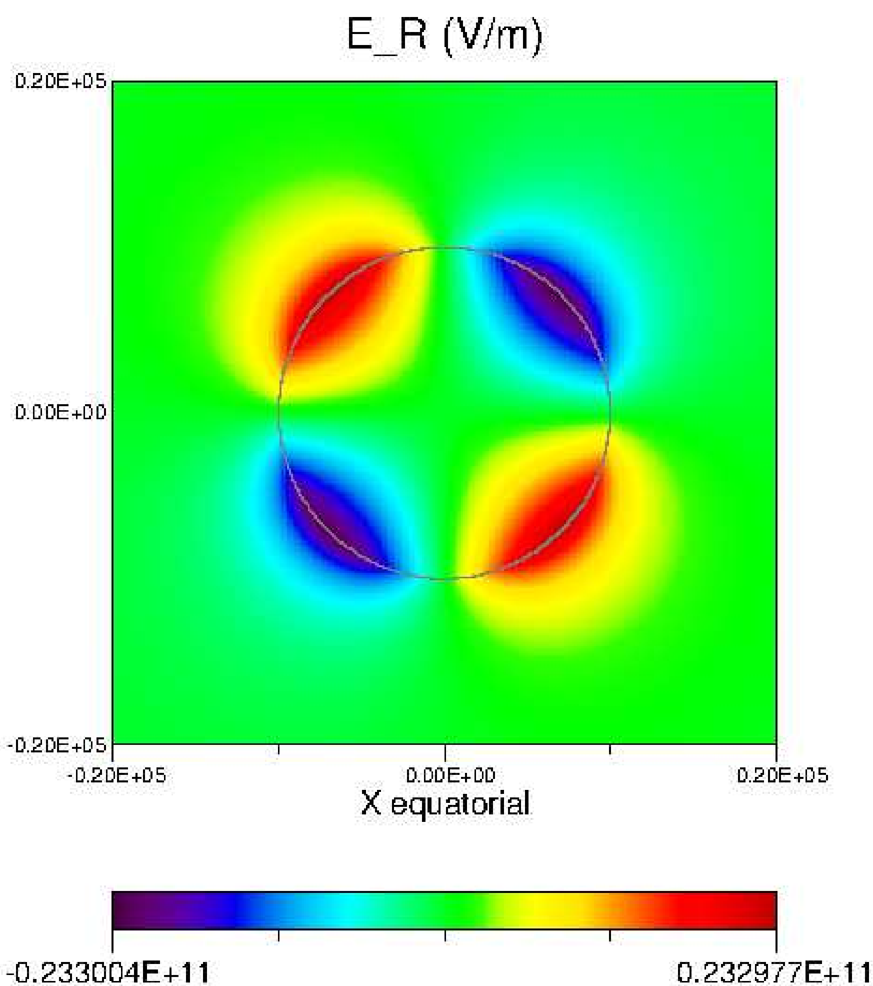
A self-consistent model : Electrosphere



Distribution of electric charge density in an electrosphere. PIC simulation.
[Spitkovsky]

- Hypothesis: negligible electric currents.
- Hypothesis: the plasma comes only from the NS surface.
- Result: Low flux of radiation.
- Result: No wind, the plasma is confined near the star.
- Result: A model for dead pulsars ?
- Result: The magnetosphere is electrically charged.

Plasma production above the NS in the polar caps



- Plasma violently accelerated above polar cap + curved trajectories (along $\vec{B}$).
- Produces synchrotron and curvature gamma rays.
- Pair production:
  $\nu_\gamma + B \rightarrow e^- + e^+$ and
  $\nu_\gamma + \nu \rightarrow e^- + e^+$.
- Production avalanche. [Sturrock 71]

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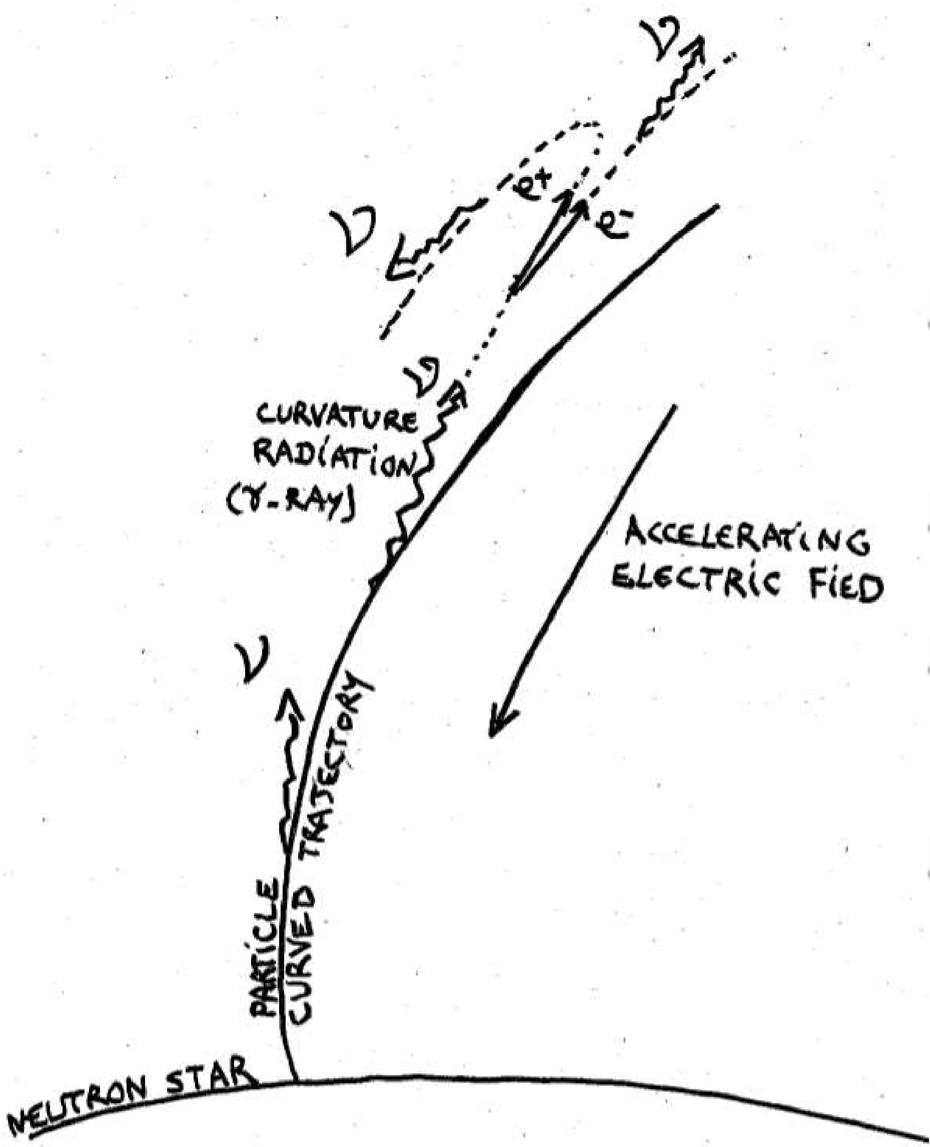

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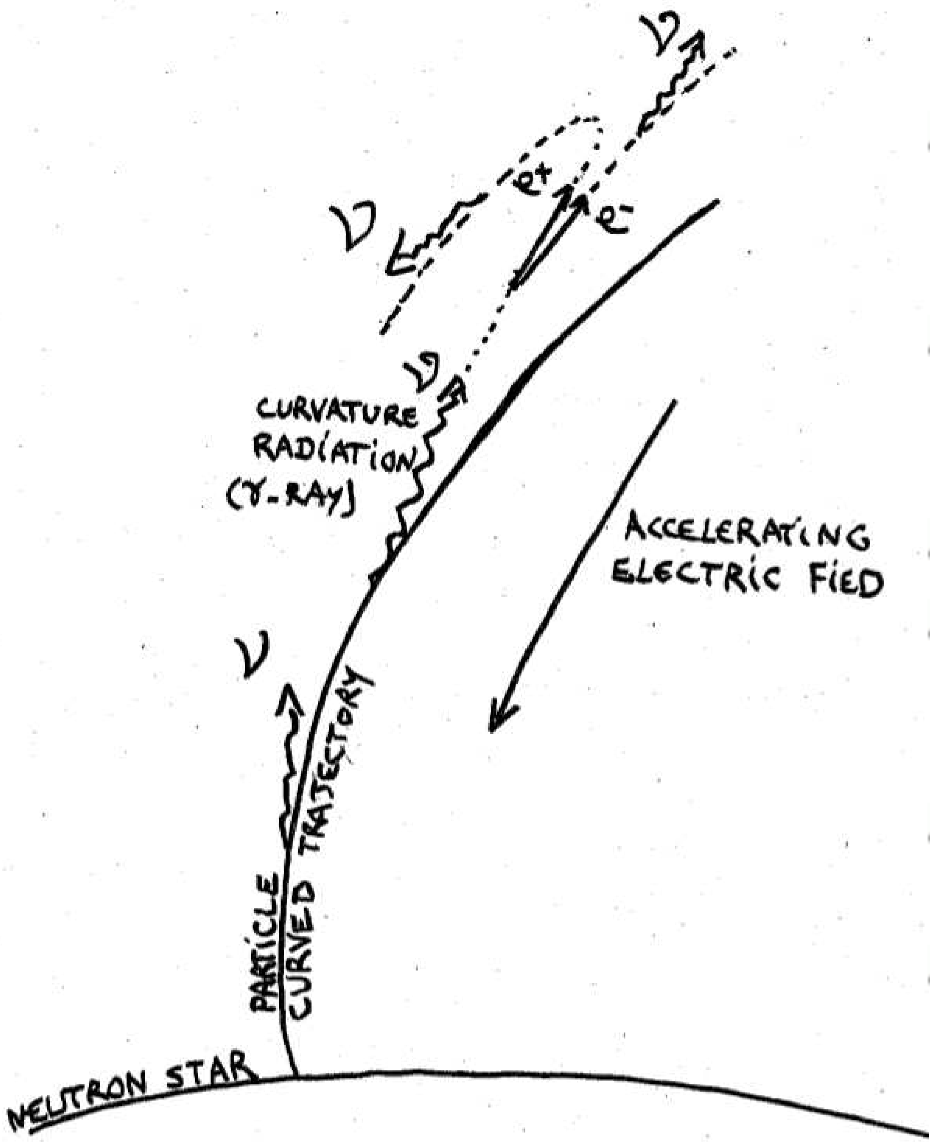
Pair production: how efficient ?

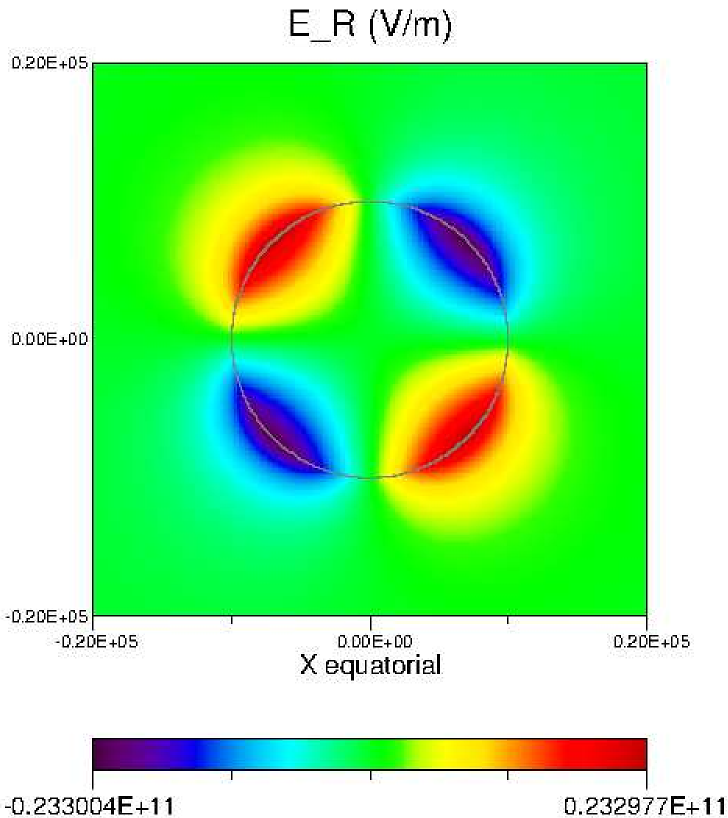


- Low density plasma = gap $\rightarrow$ accelerating electric field + e^-, e^+ pairs production.
- Produced plasma $\rightarrow$ screening of electric field. Reduction of acceleration and pair production.
- Sharp limit. Pair creation front.
- Optimistic prospect: $n_e = 1000 \times n_{primary}$. OK/observations.
- Pessimistic prospect: $n_e = 1 - 10 \times n_{primary}$. Not enough.
- Time variability ? Many regimes ? Instabilities ? [Tikonchuk 08]

Pair production: two opposite approximations

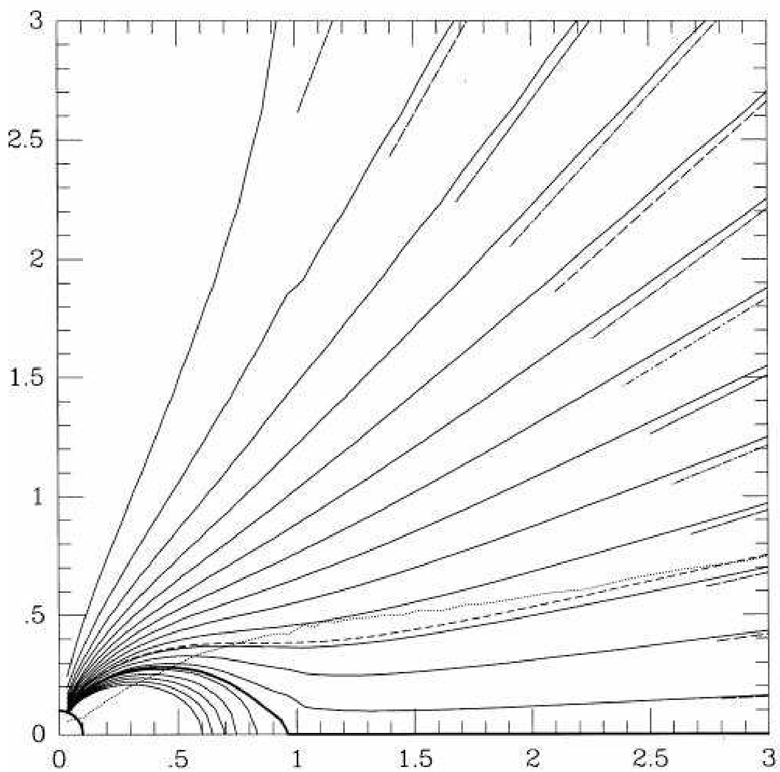
- Inefficient pair production simplified into: no pair creation.
  Solution: strong electric fields, *electrosphere*.
- Efficient pair creation simplified into: as much plasma as necessary to sceen any parallel electric field.
  Solution: *force-free magnetosphere*.

Force-free magnetosphere: hypothesis



- Φ potential drop above the surface generates dense plasma taken from the NS surface.
- There is enough plasma (very mobile along $\vec{B}$) to short-circuit the parallel electric field (in RF), $\vec{E}_{RF} \cdot \vec{B}(\vec{r}) = 0$.

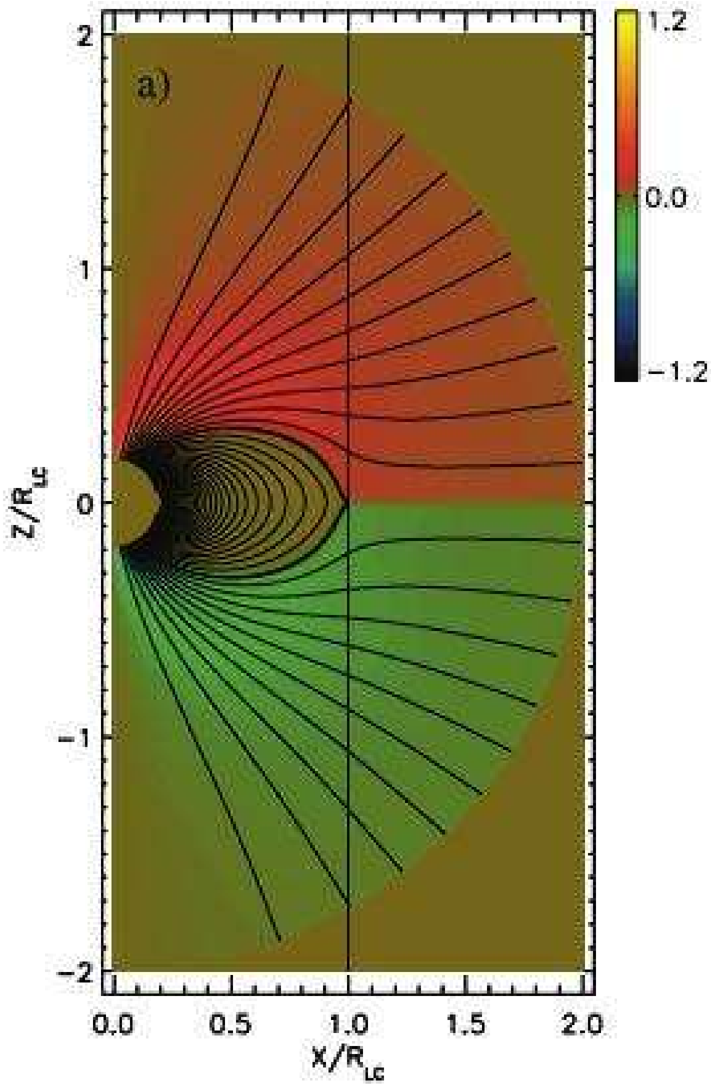
Force-free magnetosphere: mathematical problem



Force-free solution. Magnetic field lines (+ asymptotic analytical solution). The Y separatrix (thick line) is also a current layer.
[Contopoulos et al.]

- Force-free equation for aligned rotator ($i = 0$):
  $(1 - \frac{s^2}{R_{LC}^2})(\frac{\partial^2\Psi}{\partial s^2} + \frac{\partial^2\Psi}{\partial z^2}) - (1 + \frac{s^2}{R_{LC}^2})\frac{1}{s}\frac{\partial\Psi}{\partial s} + I(\psi)\frac{\partial I}{\partial\psi}$
  where $s =$ cylindrical distance from rotation z axis, Ψ: magnetic flux enclosed in circle of radius s. [Michel 1973, Scharleman, Wagoner 1973]
- Solved only in 1999 ! [Contopoulos et al.]

Force-free magnetosphere: solution for an aligned pulsar ($i = 0$)

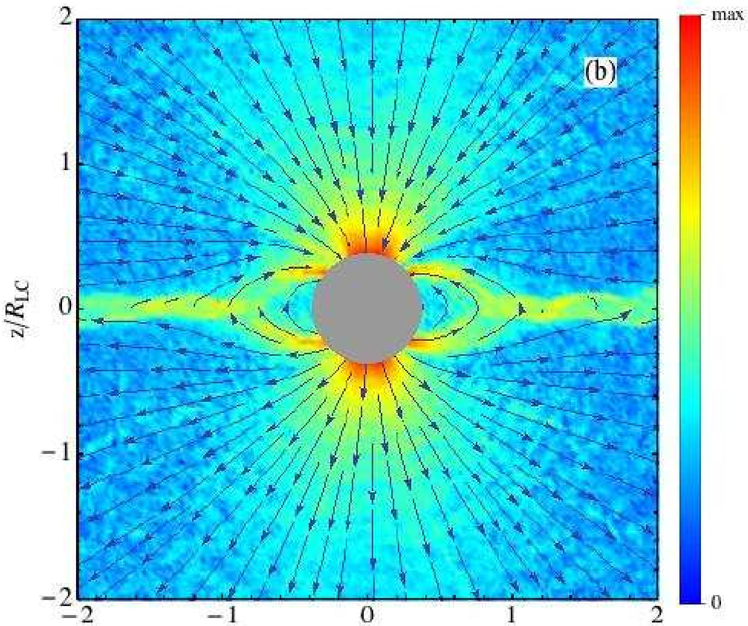


Magnetic field lines and (color) azimuthal B_ϕ

[Spitkovsky 14 (astro-ph)]

- At large distances, like a split monopole. (Magnetic field lines almost radial.)
- A Y shaped current layer. Solutions parametrised by $R_Y/R_{LC} < 1$.

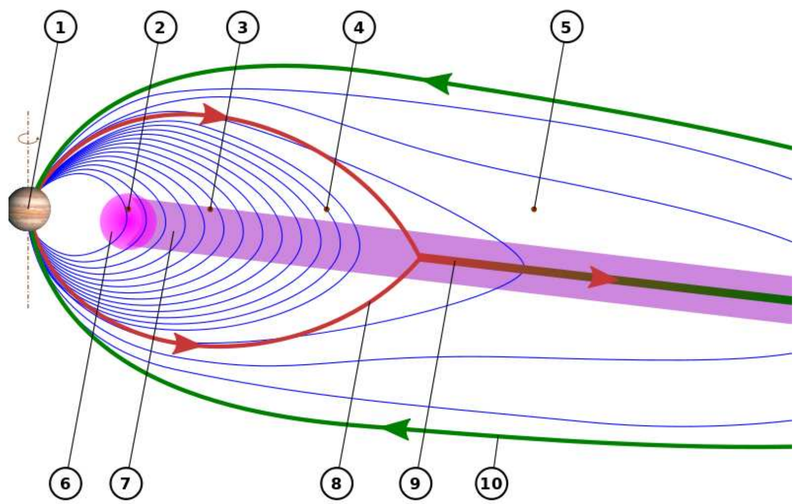
Force-free magnetosphere: solution for an aligned pulsar ($i = 0$)



Magnetic field lines and (color) current density J
[Philippov & Spitkovsky 14]

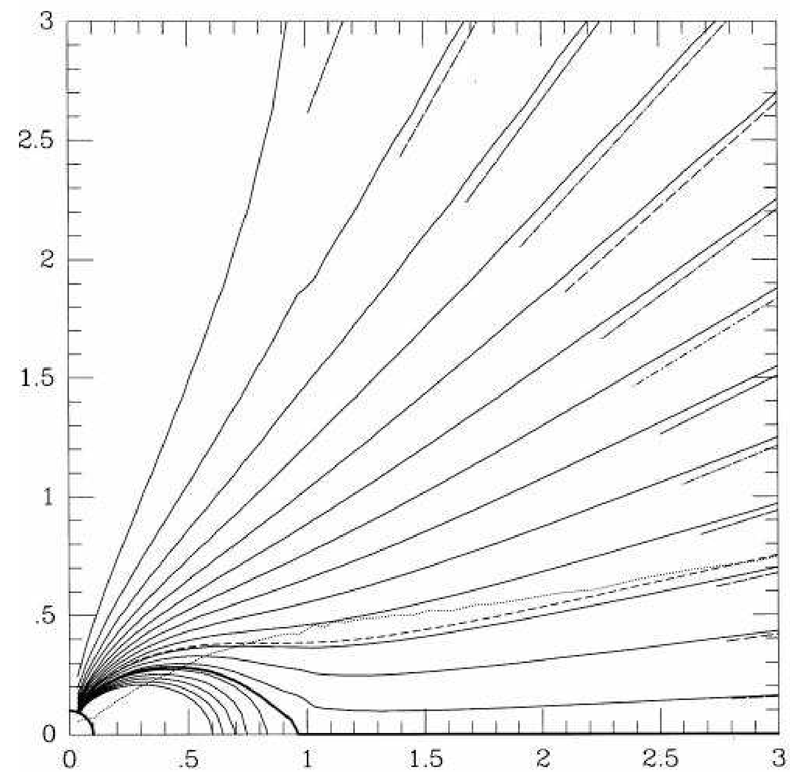
- At large distances, like a split monopole. (Magnetic field lines almost radial.)
- A Y shaped current layer. Solutions parametrised by $R_Y/R_{LC} < 1$.

A quick comparison with Jupiter magnetosphere



Scheme of the magnetosphere of Jupiter

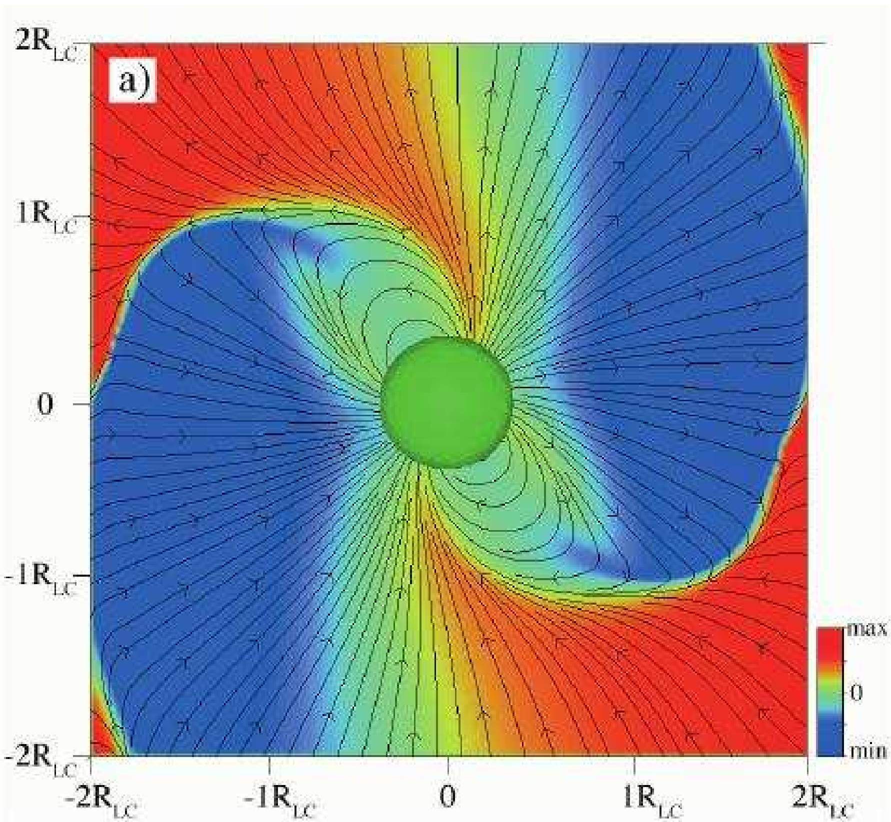
[Edward, Bunce, Cowley 01]



Force-free pulsar magnetosphere ($i = 0$)

Contopoulos + 99]

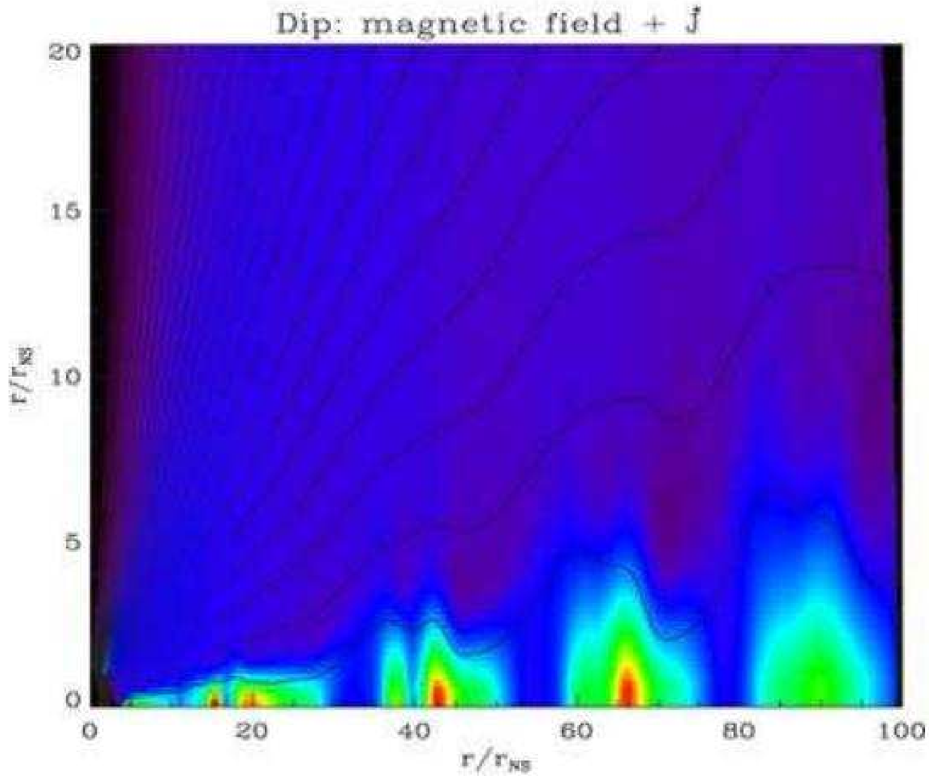
Oblique force-free magnetosphere ($i \neq 0$)



Poloidal field lines
and (color) azimuthal B_Φ.
[Spitkovski 06]

- Time dependent model + numerical resistivity.
  [Spitkovski 06, Bucciantini 06 Komissarov 06]
- Like the aligned pulsar, but the shape is modulated by the rotation;
- A Y shaped current layer $R_Y/R_{LC} \sim 1$.
- Loss of rotational energy $\dot{E}_{rot} = \mu^2 \Omega_*^4 c^{-3} (1 + \sin^2 i)$.
- The charge density above the polar cap is smaller than ρ_{GJ} (outside the rotation axis).

Dynamical force-free magnetosphere ($i = 0$)

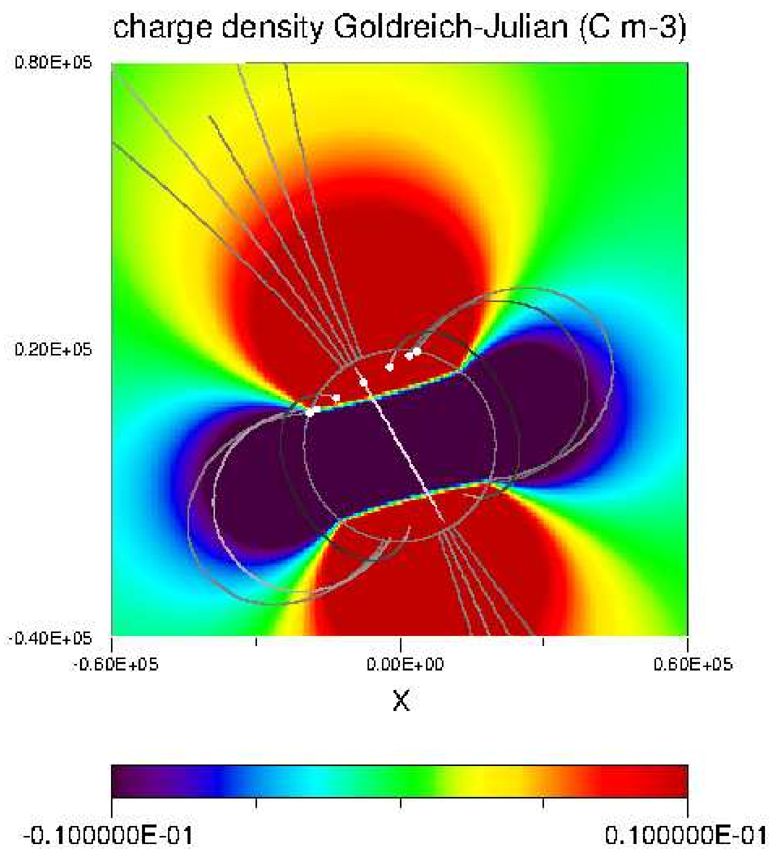


[Bucciantini 06]

MHD simul. of aligned force-free Msphere. Color: angular momentum density. Blobs of reconnected plasma. [Bucciantini 06]

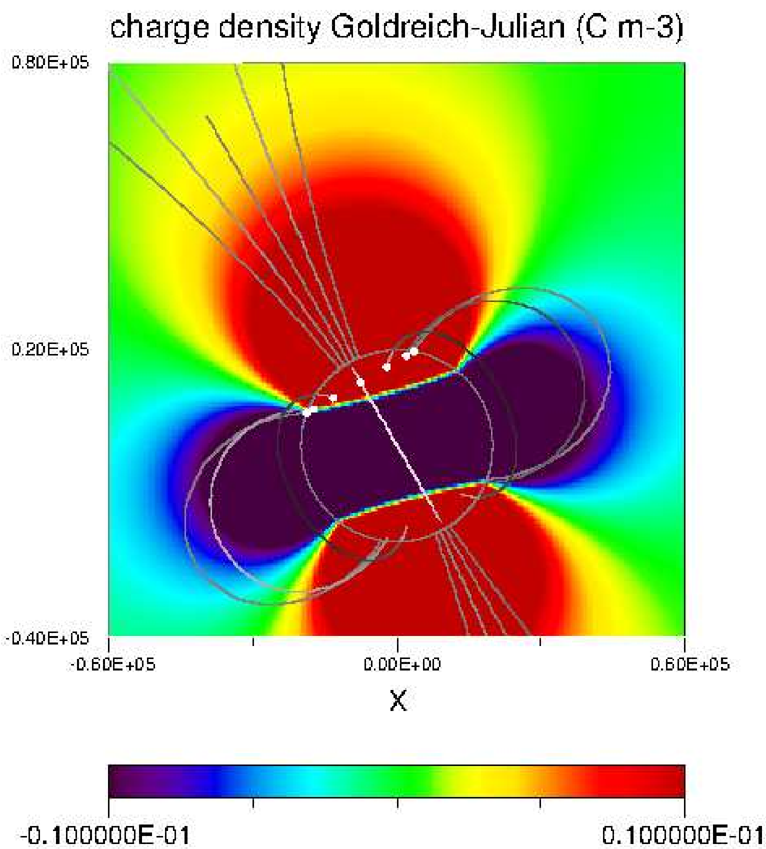
- Reconnection along the current layer beyond the lignt cylinder.
- Blobs of plasma, X-lines.
- In a relativistic e^-, e^+ plasma, efficient source of acceleration, power law -2. [Spitkovsky APJL 14]
- (!) All these studies based on numerical simulations of resistive/viscous plasma : favors reconnection / real energetic plasmas. (Like simulating a turbulence in a river with a flow of honey.)

Solar system vs PSR



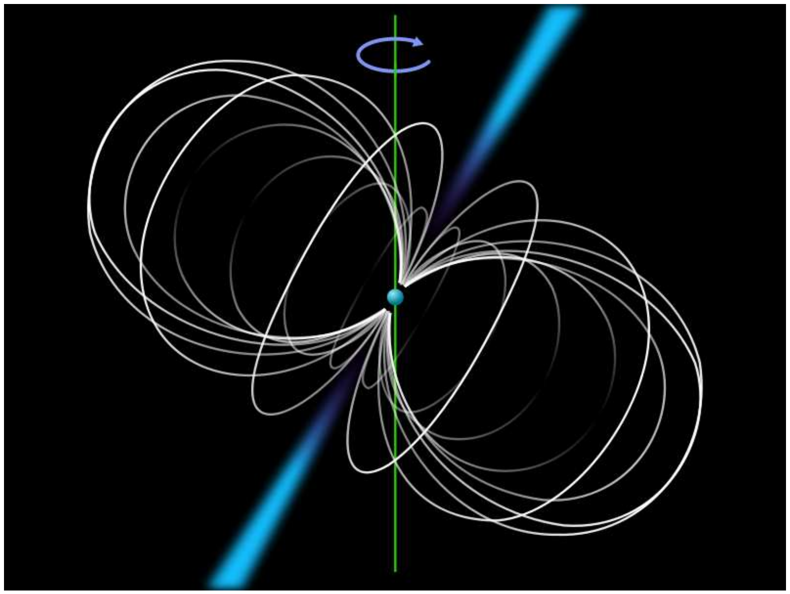
- In Solar system, ρ_{GJ} negligible ($x.10^{-y}$ cm^{-3} for Jupiter)
- In Earth AAR, no synchrotron, $\mu \neq 0 \implies$ Knight effect.
- In PSR, $\mu = 0 \implies$ no mirror force, and no Knight effect.
- In AZ, forced current. In PSR, forced electric potential drop.
- If strong double layers (DL) present in both cases, not the same causes, and not the same physical conditions.

Radio waves: cyclotron maser instability (CMI) ?



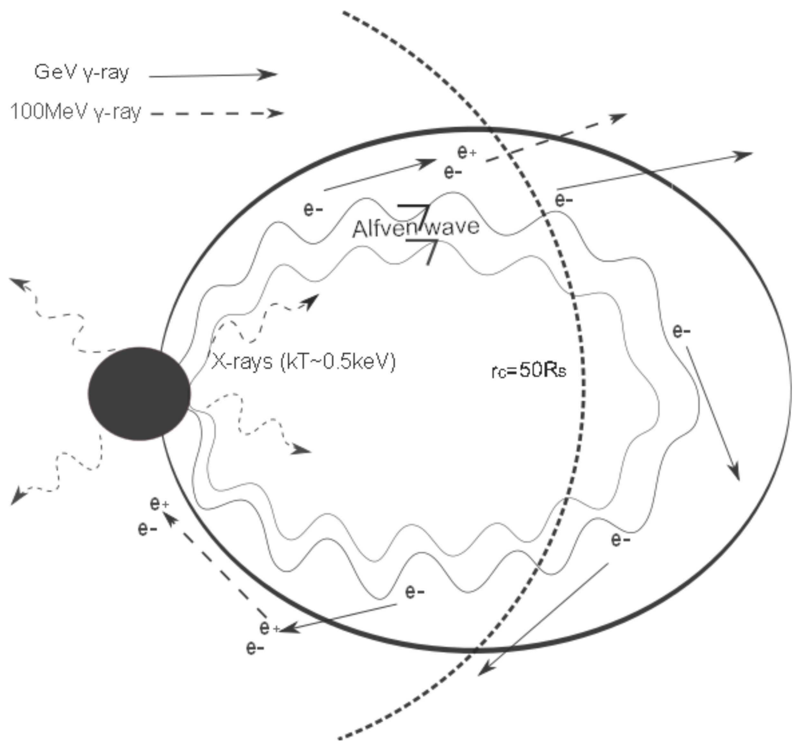
- In AAR, no synchrotron, $v_\perp \neq 0$.
- Electron distributions (shells, rings, loss cone) unstable to CMI.
- In PSR, $v_perp = 0 \implies$ no such distribution.
- The CMI theory is not directly applicable to radio emissions from pulsars.

Acceleration by ALfvén waves (AW) ?



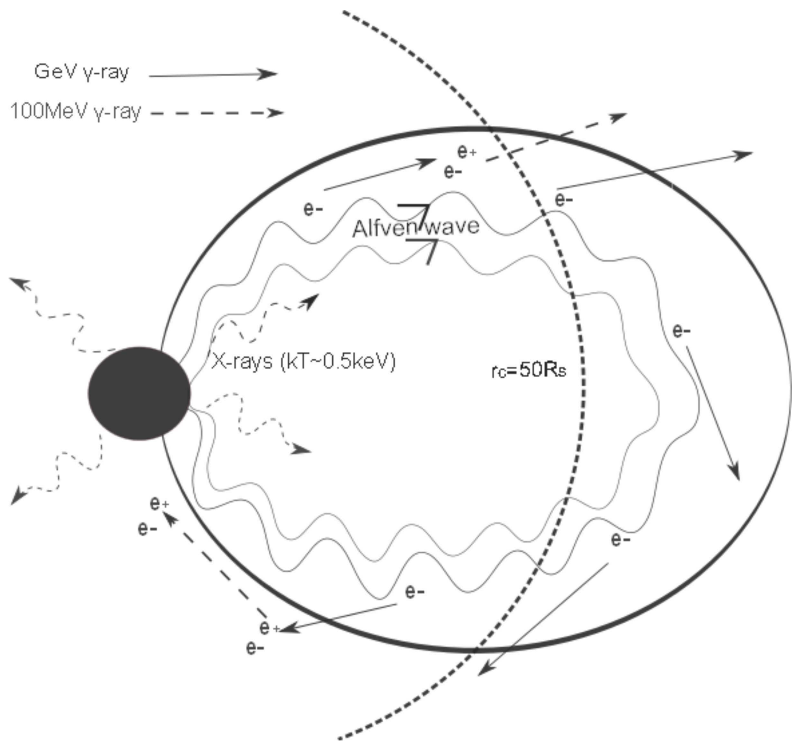
- As for the Earth, on the surface, $\vec{B}$ is static.
- No source of AW from the ground.
- On Earth, AW come from perturbations of the tail and magnetopause, because of the flux of energy from the solar wind.
- In an isolated pulsar, no strong external disturbance.
- Acceleration by AW not investigated, and not expected on isolated pulsars.

Acceleration by ALfvén waves (AW) on magnetars



- X and γ ray flares form very magnetized young PSR called magnetars.
- As for other neutron stars, the surface is a solid crust.
- Star-quakes on magnetars.
- Magnetic field frozen onto the crust.
- A star-quake is a source of AW with huge energy.
- Acceleration by these AW
- Synchrotron and curvature radiation : star-quakes trigger X and γ ray flares.

Conclusion



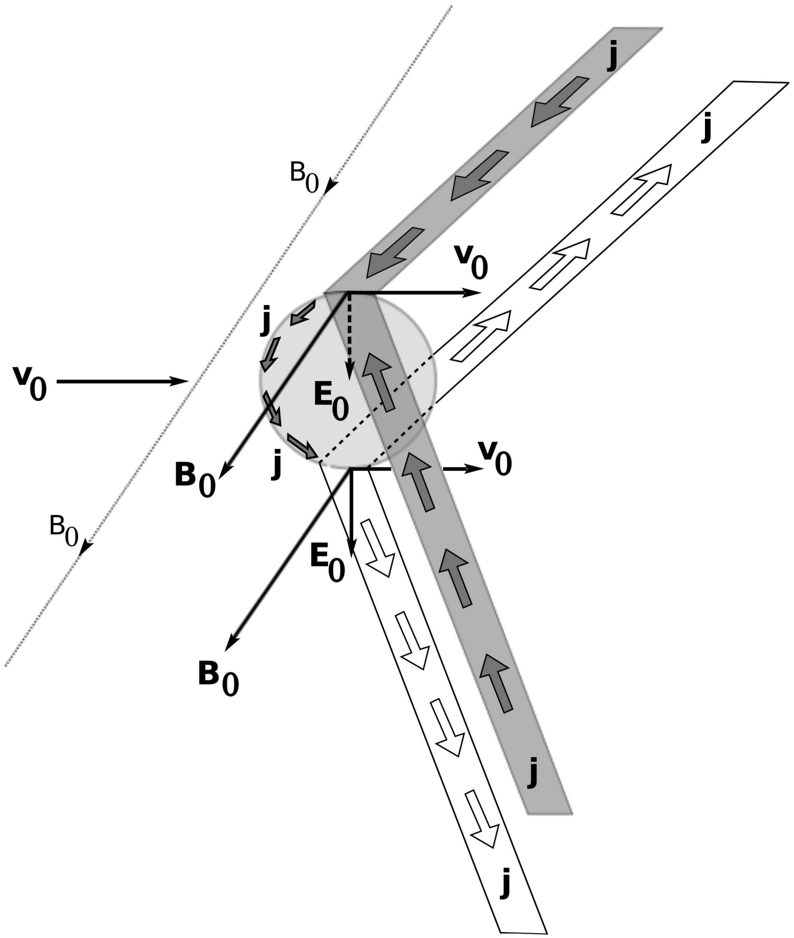
A very different micro-physics

- Highly relativistic particles;
- High energy radiation (synchrotron, curvature radiation);
- Plasma creation (e$^-$ e$^+$ pairs).
- Magnetic moment $\mu = 0$.

Macro-physics

- With rotationally powered pulsars (standard case), energy input is neutron star rotation *only*.
- Double layers, but with other principles (no mirror force, pair creation front);
- Radio emission, but no CMI (because no perpendicular velocity distribution);
- More analogy expected with AW acceleration during star-quakes.

Et les planètes de pulsars ?



- On connaît 5 systèmes planétaires
- On suspecte 2 systèmes d'astéroïdes
- On se sait pas si le vent du pulsar est super ou sous-Alfvénique.
- Donc soit une Msphère derrière un choc.
- Soit le vent atteint la planète. inducteur unipolaire + Aile d'Alfvén, comme Io et Ganymède dans le plasma de Jupiter.
- Clin d'oeil : Fast Radio Burst : une impulsion radio isolée, dispersion $\rightarrow$ distance ~ 500 Mpc.
- P. Zarka et moi pensons qu'un FRB peut provenir d'une planète de pulsar.
- Se serait alors le signal planétaire d'origine la plus lointaine (distance cosmologique !)