Neutron stars:
macroscopic objects with quantum properties

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Outline

Avertissement

Toute ressemblance avec des étoiles réelles, existantes ou ayant existé ne saurait être que pure coïncidence.

Brief overview

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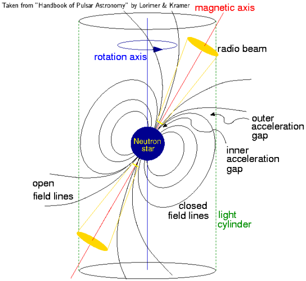

Figure: A pulsar.
(Lorimer & Kramer, 2004)

Indisputable observations

- rotation period $P \in [1.5\ ms, 10\ s]$.
- derivative of period $\dot{P} \in [10^{-18}, 10^{-15}]$.
- slowdown by rotational braking constrained by

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

$I \approx 10^{38}\ \mathrm{kg.m^2}$: moment of inertia.

A doubtful interpretation

- magnetic field estimated by magnetodipole losses

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

$\Rightarrow$ only constrain $B_\perp = B\ \sin\chi$.

$\Rightarrow$ do not believe these estimates.

$\Rightarrow$ B around $B_{\rm qed} = 4.4 \times 10^9$ T.

$\Rightarrow$ electrodynamics requires QED.

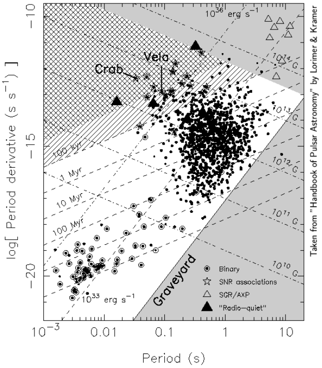

Figure: $P - \dot{P}$ diagramm.
(Lorimer & Kramer, 2004)

Neutron star magnetosphere

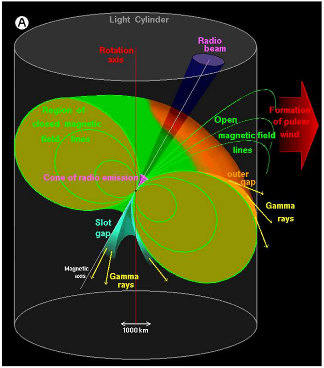

Figure: The standard pulsar model.

Radiation mechanisms and sites

- thermal, synchrotron, inverse Compton, curvature.
- radio photons from polar caps.
- high-energy photons from slot/outer gaps because high magnetic opacity at small radii.

Electrodynamics

- magnetosphere filled with a quasi-neutral (pair?) plasma.
- pair creation in the polar caps.

$\Rightarrow$ source of particles for the wind and nebula.

- are protons/ions also present?
- wind radially expanding outside the light-cylinder.

Do pulsars get on well with magnetic fields?

Radio emission requires

- a intense magnetic field for the reaction: $B + \gamma \to e^{\pm}$.
- a pair cascade $e^{\pm}$ for the reaction: $1\ e^{\pm} \to N_1\ \gamma \to N_1\ N_2\ e^{\pm}$

But

- a strong magnetic field $B > B_{\rm qed}$ inhibits radio emission
- thus pair creation efficiency.
- may be due to photon splitting according to $B + \gamma \to \gamma_1 + \gamma_2$

$\Rightarrow$ radio emission disappears.

$\Rightarrow$ the theory tells us that neutron stars at $B > B_{\rm qed}$ are no more radio pulsars.

$\Rightarrow$ let us call them magnetars.

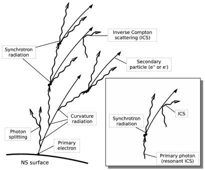

Figure: Pair cascade

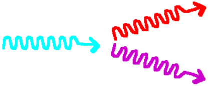

Figure: Photon splitting.

High B-pulsars B ($> B_{\mathrm{edq}}$)

Radio emission detected from several pulsars

- PSR J1847-0130: 9.4×10^9 T (McLaughlin et al., 2003).
- PSR J1718-3718: 7.4×10^9 T (Kaspi & McLaughlin, 2005).
- PSR J1846-0258: 4.9×10^9 T (Gotthelf et al., 2000).

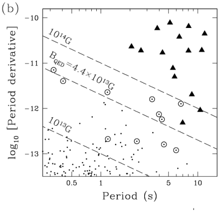

Figure: High-B pulsars. (Ng et al., 2011)

Low B-magnetars B ($< B_{\mathrm{edq}}$)

Magnetars with pulsar properties and low field exist

- SGR 0418+5729: 6×10^8 T (Rea et al., 2010)
- SGR 1822-1606: 2.7×10^9 T (Rea et al., 2012)
- 3XMM J1852+0033: $< 4.1 \times 10^9$ T (Rea et al., 2014)

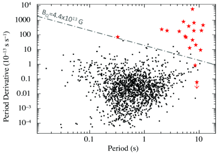

Figure: Low-B magnetars. (Rea et al., 2012)

- Is the value $B_{\rm qed} \approx 4.4 \times 10^9$ T really discriminating?
- Is the B field reliably determined?
- What is the influence of gravitation on B-field and QED processes?

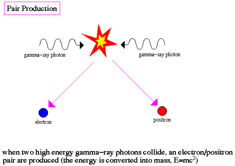

Figure: Pair production.

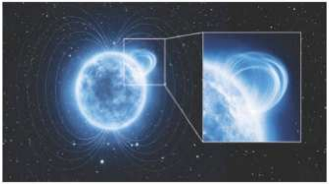

Figure: Artist view of a magnetar.

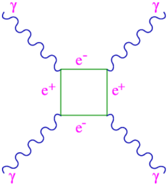

Figure: Photon scattering.

An accurate and quantitative analysis of phenomena at the neutron star surface takes into account

- an important space time curvature.
- a magnetic field strength of the order or larger than $B_{\rm qed}$.
- a relativistic pair plasma $e^{\pm}$ (classical/quantum?).
- high-energy radiation processes (curvature, synchrotron, inverse Compton).

Therefore it requires

- QED processes: pair creation, quantum radiation.
- general relativity: light bending, gravitational redshift.

Space-time in 3+1 formalism

A first approach starts with an effective theory for the electromagnetic field including

- quantum corrections
- gravitational corrections

to Maxwell equations.

Assumptions

- 3+1 foliation of spacetime based on general relativity.
- Lagrangian description of the electromagnetic field.

The metric is divided in a 3D space Σ_t and a time coordinate

$$ds^2 = \alpha^2 \, c^2 \, dt^2 - \gamma_{ab} \, (dx^a + \beta^a \, c \, dt) \, (dx^b + \beta^b \, c \, dt)$$

with

- lapse function α.
- shift vector β.
- spatial metric γ_{ab}.

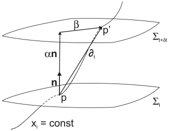

Figure: Space-time split in 3+1.

The QED Lagrangian

- I^i, A_i: 4-current and 4-potential.
- F^{ik}: electromagnetic tensor.
- $\mathcal{I}_1 = F_{ik}\,F^{ik}$, $\mathcal{I}_2 = F_{ik}\,{}^*F^{ik}$ field invariants.

$$\mathcal{L}_{\rm QED} =$$

- QED Lagrangian

	Euler-Heisenberg	Born-Infeld
η_1	$\frac{\alpha_{\rm sf}}{180\,\pi}\,\frac{1}{2\,\mu_0\,B_{\rm qed}^2}$	$\frac{1}{32\,\mu_0\,b^2}$
η_2	$\frac{7}{4}\,\eta_1$	η_1

with $\alpha_{\rm sf}$ the fine structure constant and $b = 9.18 \times 10^{11}$ T.

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$$\mathcal{L}_{\rm QED} = -\frac{1}{4\,\mu_0} F_{ik} \, F^{ik} - I^i \, A_i +$$

- QED Lagrangian
- Classical terms

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$$\mathcal{L}_{\rm QED} = -\frac{1}{4\,\mu_0} F_{ik} F^{ik} - I^i A_i + \eta_1 \mathcal{I}_1^2 + \eta_2 \mathcal{I}_2^2$$

- QED Lagrangian
- Classical terms
- QED corrections à la Euler Heisenberg .

	Euler-Heisenberg	Born-Infeld
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- time evolution from the variational principle

$$\frac{\partial \mathcal{L}_{\rm QED}}{\partial A_i} - \frac{1}{\sqrt{-g}} \, \partial_k \sqrt{-g} \, \frac{\partial \mathcal{L}_{\rm QED}}{\partial \partial_k A_i} = 0$$

- constitutive relations for GRQED ($\xi_1 = 1 - K \, \eta_1$ and $\xi_2 \propto \eta_2$)

QED relations

$$\mathbf{F} = \xi_1 \, \mathbf{D} + \frac{\xi_2}{c} \, \mathbf{B}$$

$$\mathbf{G} = \xi_1 \, \mathbf{H} - \frac{\xi_2}{c} \, \mathbf{E}$$

GR relations

$$\varepsilon_0 \, \mathbf{E} = \alpha \, \mathbf{D} + \varepsilon_0 \, c \, \beta \times \mathbf{B}$$

$$\mu_0 \, \mathbf{H} = \alpha \, \mathbf{B} - \frac{\beta \times \mathbf{D}}{\varepsilon_0 \, c}$$

Homogeneous Maxwell equations

$$\nabla \cdot \mathbf{F} = \rho$$

$$\nabla \times \mathbf{G} = \mathbf{J} + \frac{1}{\sqrt{\gamma}} \, \partial_t (\sqrt{\gamma} \, \mathbf{F})$$

Inhomogeneous Maxwell equations

$$\nabla \times \mathbf{E} = -\frac{1}{\sqrt{\gamma}} \, \partial_t (\sqrt{\gamma} \, \mathbf{B})$$

$$\nabla \cdot \mathbf{B} = 0$$

GR and QED seen as material media in standard classical Newtonian theory.

(Pétri, 2015a)

For a $e^{\pm}$ pair plasma

- infinite conductivity $\sigma = +\infty$.
- zero temperature $T = 0$ thus zero pressure.
- negligible mass $m_e = 0$.

Force-free approximation

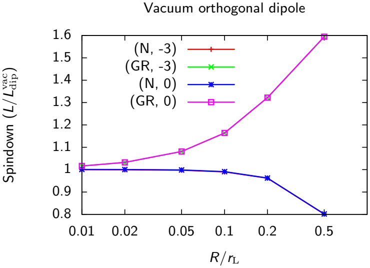
$$\mathbf{J} \cdot \mathbf{E} = 0$$
$$\rho\,\mathbf{E} + \mathbf{J} \times \mathbf{B} = \mathbf{0}$$

Electric current

$$\mathbf{J} = \rho\,\frac{\mathbf{E} \wedge \mathbf{B}}{B^2} + \frac{\mathbf{B} \cdot \nabla \times \mathbf{G} - \mathbf{F} \cdot \nabla \times \mathbf{E}}{B^2}\,\mathbf{B}.$$

Maxwell equations are complete, the charge density ρ adapting to the field configuration.

Vacuum and force-free GRQED dipole



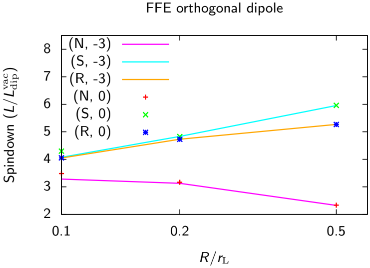


Figure: Spindown luminosity for different rotation rates, magnetic field strengths given by $\log(B/B_q)$ and gravitational field (Newtonian or GR).

(Pétri, 2016)

QED has no impact on spindown luminosity. Also true for FFQED.

Possible applications of QED

- dynamics of neutron star magnetospheres
  $\Rightarrow$ spindown luminosity, no effects.
- wave propagation quantum/relativistic plasmas
  $\Rightarrow$ vacuum birefringence, signature from optical?
  (Mignani et al., 2017)
- X-ray polarisation prediction (Weisskopf et al., 2016).
  $\Rightarrow$ an observable for the future IXPE mission.
- do photons follow curved field lines (magnetic lensing)?
  (Shabad & Usov, 1984), (Shaviv et al., 1999)
- do we need QMHD and chiral MHD?
  (Haas, 2005), (Boyarsky et al., 2015)
- as a long term task, possibility to test QED in strong magnetic AND gravitational fields.

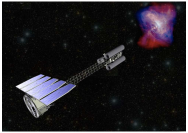


Figure: The IXPE satellite.

THANKS

FOR

YOUR ATTENTION

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Outline

- Why to study them?
- Link to nebula
- Orders of magnitude

Why study neutron stars?

The discovery of pulsars (Hewish et al., 1968) was a revolution in astrophysics and revived the theoretical study of neutron stars.

Many progresses in (astro)physics

- confirmation of the existence of neutron stars.

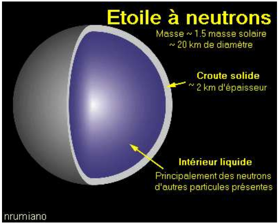

Figure: Simplified structure of a neutron star.

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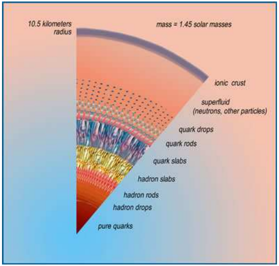

Figure: Interior of a neutron star.

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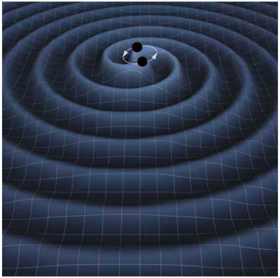

Figure: Double neutron star system.

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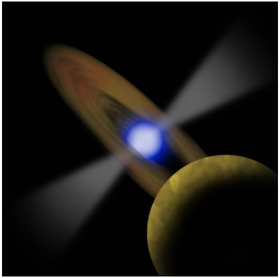

Figure: Planets around pulsars.

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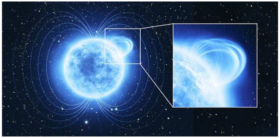

Figure: Magnetic reconnection in a magnetar.

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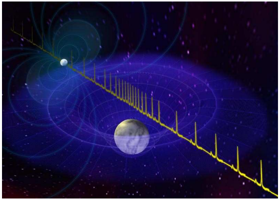

Figure: General-relativistic effects (Shapiro delay).

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- survey of the interstellar medium in the Milky Way.

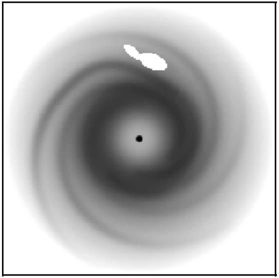

Figure: Map of the electronic density in the Milky Way.

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- survey of the galactic magnetic field in the Milky Way.

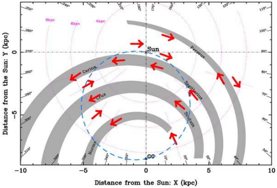


Figure: Map of the magnetic field in the Milky Way.

⇒ Important to better understand neutron star physics and especially pulsars.

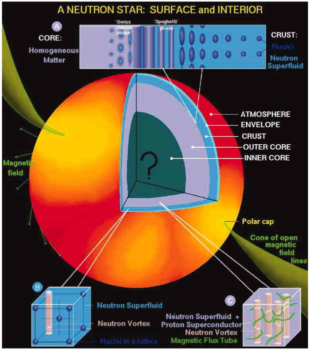


Figure: Interior view of a neutron star.

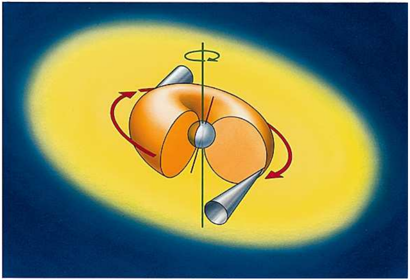


Figure: Larousse (french dictionary) view of a pulsar.

But from thermal X-ray blackbody radiation from surface, inferred magnetic field strength is 100 times stronger and polar cap area 100 smaller than expections from a dipole.

$\Rightarrow$ needs for multipolar components.

For any magnetic multipole of order ℓ, useful observables are

- the spindown luminosity (different from magnetodipole losses)

$$L \propto B^2 \, \Omega^{2\,\ell+2} \, R^{2\,\ell+4} \tag{6}$$

- the braking index n (a measure of the efficiency of braking) such that

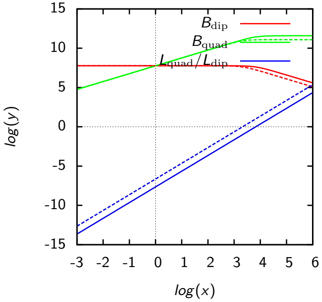
$$\dot{\Omega} = -K \, \Omega^n \tag{7}$$

For a multipole of order ℓ it becomes approximately $n = 2\,\ell + 1$.

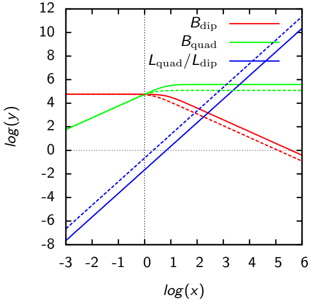
- for a dipole $n = 3$.
- for a quadrupole $n = 5$ (the same for gravitational radiation).

Magnetic field strength estimates

- luminosity L, stellar radius R and period P (or Ω) being known, we cant get an estimate of the magnetic field strength at the surface.
- usually done for a pure dipole.
- but if multipoles are present, the estimate becomes inaccurate or even wrong.



Normal pulsar $L_{\rm dip} \gg L_{\rm quad}$.



Millisecond pulsar $x = B_{\rm quad}/B_{\rm dip}$.

Magneto-dipole losses useless to get drastic upper limits for multipole components.

$L_{\rm dip} \gg L_{\rm quad} \not\Leftrightarrow B_{\rm dip} \gg B_{\rm quad}$ (Pétri, 2015b)

Pulsar	Distance (kpc)	Period P (s)	$\dot{P}$ (10^{-15})	Braking de index n	References
B0531+21	2.0	0.033	421	2.509 ± 0.001	Lyne et al. (1993)
J0537-6910	51	0.0161	0.0518	-1.5 ± 0.1	**?**
B0540-693	51.5	0.050	479	2.140 ± 0.009	Livingstone et al. (2005)
B0833-45	0.29	0.089	124	1.40 ± 0.20	Lyne et al. (1996)
B1509-58	5.81	0.150	1490	2.837 ± 0.001	Kaspi et al. (1994)
J1846-0258	5.10	0.325	7083	2.65 ± 0.01	Livingstone et al. (2006)
				2.16 ± 0.13	Livingstone et al. (2011)
J1119-6127	8.40	0.408	4021	2.91 ± 0.05	Weltevrede et al. (2011)
J1734-3333		1.170	2280	0.9 ± 0.2	Espinoza et al. (2011)
J1833-1034				1.857	Roy et al. (2012)
J1640-4631	12	0.206	975.8	3.15	**?**

Table: Observational properties of some typical pulsars.

Braking index: theory

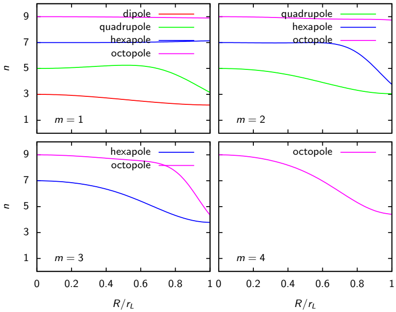


Figure: Braking index of rotating magnetic multipoles.(Pétri, 2015b)

$$\frac{R}{r_L} = \frac{\Omega R}{c} \propto \Omega \propto 1/P \quad (8)$$

- $1 < n < 3 \Rightarrow$ topology between monopolar wind and dipolar radiation.
- $3 < n < 5 \Rightarrow$ topology between dipolar and quadrupolar radiation.

Outline

- Why to study them?
- Link to nebula
- Orders of magnitude

- the pulsar and its magnetosphere,
  source of *relativistic* $e^{\pm}$ *pairs*
  $r_{\rm L} = 10^6$ m.

Figure: Link between the pulsar and 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.

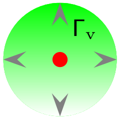
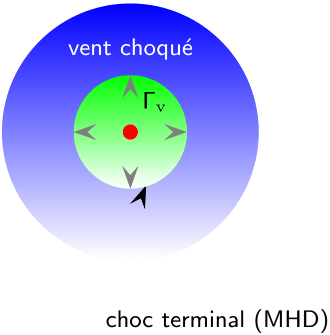


Figure: Link between the pulsar and its surrounding nebula.

Supernova remnant and 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.



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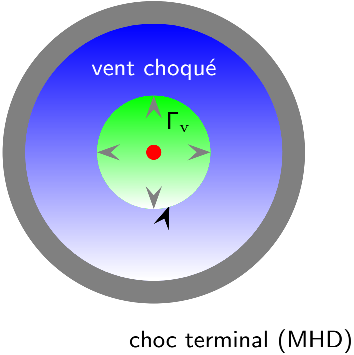

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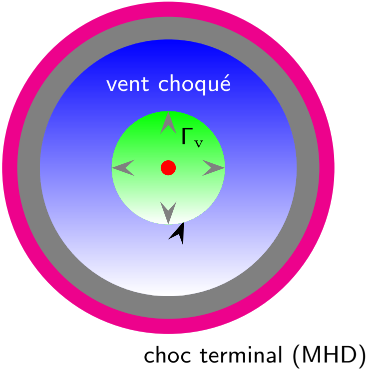

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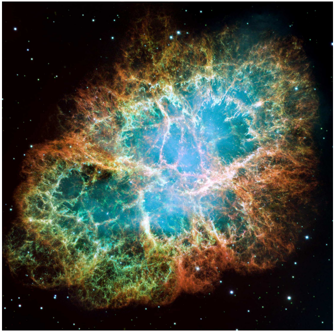

Figure: The Crab nebula.

Outline

- Why to study them?
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Orders of magnitude

Electromagnetic field

- electric field induced at the stellar crust

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

$\Rightarrow$ instantaneous acceleration at ultra-relativistic speeds ($\tau_{\mathrm{acc}} < 10^{-20}$ s).

$\Rightarrow$ Lorentz factor $\gamma \gg 1$.

Gravitational field

- negligible gravitational force !
  For proton with mass m_p

$$\frac{F_{\mathrm{grav}}}{F_{\mathrm{em}}} \approx \frac{G \, M \, m_p / R^2}{e \, \Omega \, B \, R} \approx 10^{-12} \ll 1 \quad (9)$$

and a factor $m_p/m_e \approx 2,000$ less for electrons.

Neutron star characteristics

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

⇒ dynamic of the magnetosphere dominated by the electromagnetic field.
⇒ gravitational field negligible to first approximation!

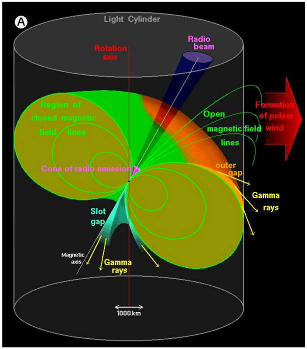

Figure: View of a neutron star magnetosphere.

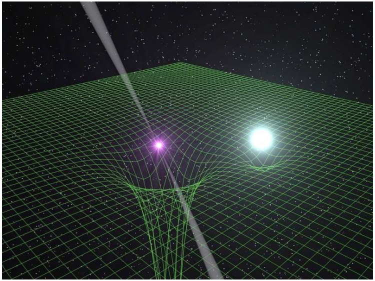

Figure: Pulsar in a gravitational field.