Le vide quantique autour des étoiles à neutrons

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Electromagnetic energy density

$$U = \vec{E}\frac{\partial L}{\partial \vec{E}} - L$$

The vacuum is Lorentz and CPT invariant :

$$L = \frac{1}{2}F + aF^2 + bG^2 + \ldots$$ where $$F = \left(\varepsilon_0 E^2 - \frac{B^2}{\mu_0}\right); \quad G = \sqrt{\frac{\varepsilon_0}{\mu_0}}\left(\vec{E}.\vec{B}\right)$$

Maxwell

$$\vec{D} = \varepsilon_0 \vec{E} + \vec{P} = \frac{\partial L}{\partial \vec{E}}$$

$$\vec{H} = \frac{\vec{B}}{\mu_0} - \vec{M} = -\frac{\partial L}{\partial \vec{B}}$$

Constitutive équations

1935-1936 Kochel, Euler, Heisenberg

$$\frac{b}{a} = 7 \qquad a = \frac{2}{45}\frac{\alpha^2\hbar^3}{m_e^4 c^5}$$

H.Euler et K.Kochel, *Naturwiss*. **23** (1935); W.Heisenberg et H.Euler, *Z. Phys.* **38** (1936) 714

$$\vec{P} = 4a\varepsilon_0 \vec{E}F + 14a\sqrt{\frac{\varepsilon_0}{\mu_0}}\vec{B}G$$

$$\vec{M} = -4a\frac{\vec{B}}{\mu_0}F + 14a\sqrt{\frac{\varepsilon_0}{\mu_0}}\vec{E}G$$

The vacuum is a non linear optical medium !

Vacuum in an external field

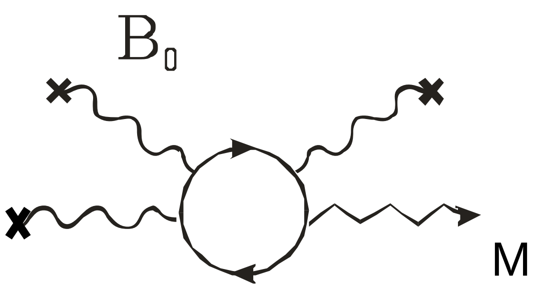
$$\vec{B}_0$$

$$\vec{P} = 0$$

$$\vec{M} = 4a\frac{B_0^2}{\mu_0^2}\vec{B}_0 = \frac{2}{45}\alpha\left(\frac{B_0^2}{B_c^2}\right)\frac{\vec{B}_0}{\mu_0}$$

where

$$B_c = m_e^2c^3/e\hbar \simeq 4.4\,10^9 \text{ T}$$



Vacuum can be magnetized !

Neutron stars

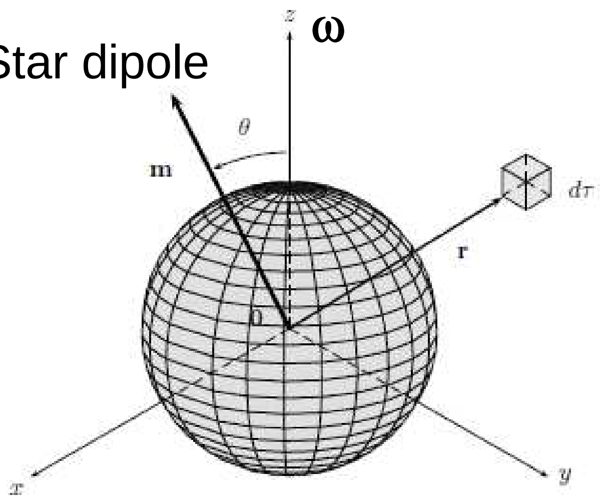
M=Solar mass

Star radius = 10 km

$B_0 > B_c$?! Magnetars

$$\mathbf{B}(\mathbf{r},t) \simeq \left(\frac{\mu_0}{4\pi}\right)\left[\frac{3\mathbf{r}(\mathbf{m}(t-r/c).\mathbf{r})}{r^5} - \frac{\mathbf{m}(t-r/c)}{r^3}\right]$$

Star dipole



$$\mathbf{dm}_{qv}(\mathbf{r},t) = \frac{\alpha B^2(\mathbf{r},t)}{2\pi B_c^2 \mu_0} f_{qv}(B^2(\mathbf{r},t))\mathbf{B}(\mathbf{r},t)d\tau$$

$$d\dot{E}_{qv} = -(\mathbf{m}(t+r/c) \times \mathbf{dB}_{qv}(\mathbf{0},t+r/c))\,\omega.\mathbf{u_z}$$

Quantum Vacuum Friction

$$\boxed{\dot{E}_{qv} \simeq \alpha \left(\frac{18\pi^2}{45}\right) \frac{\sin^2\theta}{B_c^2 \mu_0 c} \frac{B_0^4 R^4}{p^2}}$$

Experimental data are : $P, \dot{P}, \ddot{P}, \dddot{P}$ rarely

often

Is QVF in contadiction with existing data ?

$$\dot{E} = 4\pi^2 I \dot{P} P^{-3}$$

I inertia moment assumed as constant in time

Classical radiation from rotating magnetic dipole :

$$\dot{E}_r = \left(\frac{128\pi^5}{3}\right) \frac{\sin^2\theta}{\mu_0 c^3} \frac{B_0^2 R^6}{p^4}$$

B_0 is given assuming that $\dot{E} = 4\pi^2 I \dot{P} P^{-3}$ = $\dot{E}_r = \left(\frac{128\pi^5}{3}\right) \frac{\sin^2\theta}{\mu_0 c^3} \frac{B_0^2 R^6}{p^4}$

$$B_0 \propto \sqrt{P\dot{P}}$$

and assuming sinθ=1

$\boxed{\text{The braking factor :}}$

$$n = \frac{\nu\ddot{\nu}}{\dot{\nu}^2} \qquad n = 2 - \frac{P\ddot{P}}{\dot{P}^2} \qquad \nu=1/P$$

Classical dipole radiation

$$\dot{\nu} = -\frac{\dot{E}_r}{4\pi^2 I\nu} = -K_r\nu^3$$ and $n_{cl}=3$!?

The problem is that no neutron star shows an n = 3 !

Thus $$\dot{E} = 4\pi^2 I\dot{P}P^{-3} \boxed{\neq} \dot{E}_r = \left(\frac{128\pi^5}{3}\right)\frac{\sin^2\theta}{\mu_0 c^3}\frac{B_0^2 R^6}{p^4}$$

!

$\boxed{B_0 \text{ ??}}$ Nobody cares ?!

QVF

$$\dot{P} = \left(\frac{32\pi^3}{3I}\right)\frac{B_0^2 R^6}{\mu_0 c^3 P} + \alpha\left(\frac{3}{16I}\right)\frac{B_0^4 R^4 P}{B_c^2 \mu_0 c}$$

Magnetars

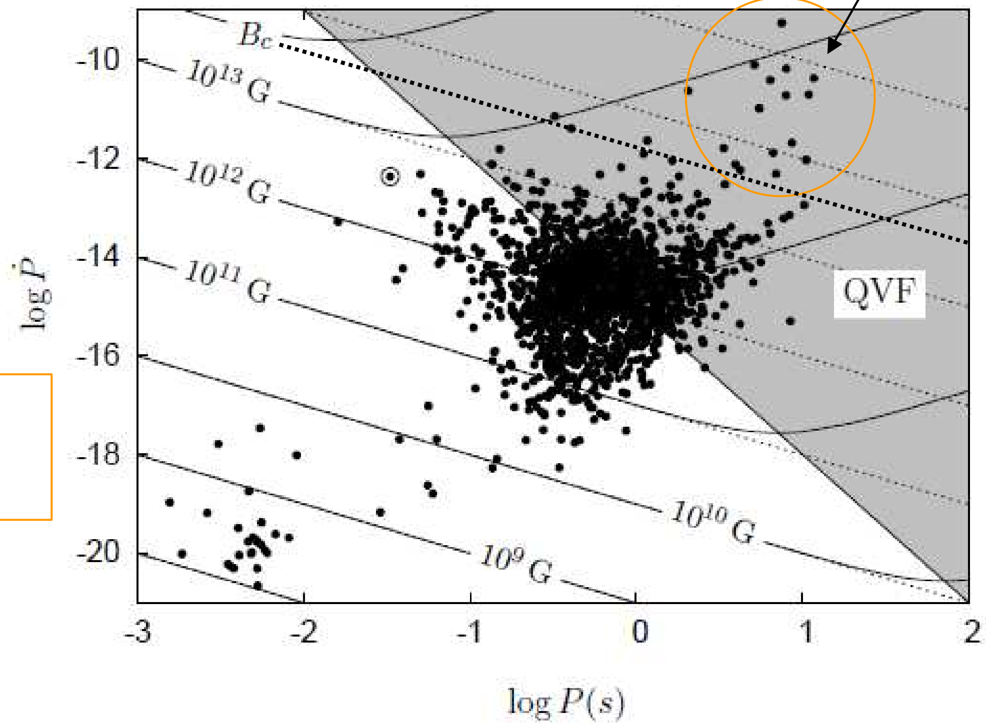


FIG. 1: $P - \dot{P}$-diagram for the currently known pulsars. Pulsars located in the upper right area (gray) have an energy loss process dominated by QVF. The Crab pulsar is marked as a circle filled with a dot.

« classical » values of B_0 ....

« QVF » values of B_0 ____________________

$$n = \frac{\nu \ddot{\nu}}{\dot{\nu}^2}$$

$$n = 2 - \frac{P\ddot{P}}{\dot{P}^2}$$

What about *n* ?

QVF can reproduce the measured valeur of *n*.

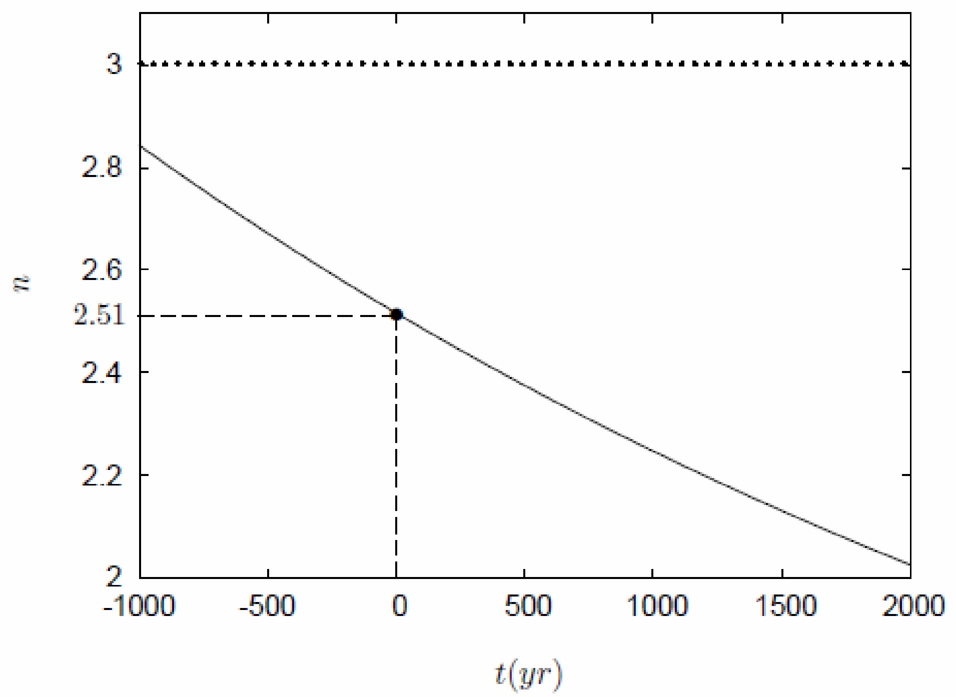


FIG. 3: Braking index of the Crab pulsar as a function of time when QVF is taken into account (full line) and when QVF is neglected (dotted line). $t = 0$ corresponds to current time.

QVF can be used to predict $\dot{n} = f\left(P, \dot{P}, \ddot{P}, \dddot{P}\right)$

For the Crab pulsar we get

$-1.8421\ 10^{-11}\ s^{-1}$ vs $1.5676\ 10^{-13}\ s^{-1}$,

whereas

for the B1509-58 pulsar we get

$-1.3550\ 10^{-11}\ s^{-1}$ vs $-1.2500\ 10^{-11}\ s^{-1}$!!!.

The only two stars in the ATNF catalogue for which $\dddot{P}$ has been measured.

There are no contadictions between existing experimental data and QVF !

Does QVF exist or not ?

We need more experimental data !

Observations of QVF in pulsars would confirm the existence of one of the very few macroscopic effects of quantum vacuum,

while

if QVF is invalidate this would indicate for the first time that the usual QED model of the quantum vacuum used to calculate the QVF effect needs to be mended.

Both issues are very important !

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