Ultra-strong Electric Fields and Vacuum Breakdown: Search for an Astrophysical Scenario

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Summary. — In some models of $\gamma$-ray bursts super-strong electric fields ($E \sim 10^{14}$ statvolt cm$^{-1}$) have been surmized. Such large fields may provide copious pair production through vacuum polarization. Here we examine various astrophysical scenarios where huge electric field can be present. It is shown that when the conditions for quantistic vacuum breakdown are met, pair creation through conventional processes is likely to be always more important. Although of great physical interest, quantum pair production seems therefore of little astrophysical relevance.

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1. – Introduction

Pair production by quantum vacuum polarization (or vacuum breakdown, VB in the following) has been invoked by some authors (e.g. [1, 2, 3, 4]) in connection with the modeling of $\gamma$-ray bursts (GRBs). However little attention was paid to the astrophysical picture where the VB condition might occur.

Here we examine various astrophysical scenarios where large electric field may be expected and explore the possibility of inducing the VB. In section 2 large B-field pulsars ("magnetars") are considered, following a proposal by Usov [5]. In section 3 the case of a magnetic field frozen in the matter accreting onto black hole is examined, and in section 4 we consider the E-field due to charge separation, induced by a flash of radiation propagating through a plasma, in the context of the GRB scenario proposed by Lieu et al [2].

Since we are interested in a preliminary assessment of the relevance of quantum pair production under astrophysical conditions, we assume that the condition for vacuum breakdown (Klein instability) is given by the semi-classical expression (see e.g. [6])

\[ eE\lambda_c = 2m_e c^2 \]
where \( \lambda_c \) is the Compton wavelength of the electron, which gives

\[
E > 2m_e c^2 / e\lambda_c = E_c \approx 2 \times 10^{14} \text{ statvolt cm}^{-1}.
\]

2. – Highly magnetized neutron stars

Huge electric fields are produced in pulsars by the rotating magnetic field entrapped in the neutron star crust.

As far as we know, the possible appearance of VB was first proposed in a remarkable paper by Usov [5]. It was suggested that GRB should be the progenitors of ultra-high magnetic field pulsars (or magnetars), proposed at about the same time by Duncan and Thompson [7] in connection with soft gamma repeaters. Usov made the rather bold, at that time, assumption that GRBs are at cosmological distances, and took as characteristic parameters for the newly formed magnetar a period \( P = 0.5 \text{ ms} \) and a B-field \( B = 3 \times 10^{15} \text{ G} \). Some years later magnetars were actually discovered and the main parameters of the prototype of this class of sources, SGR 1806-20 [8], are \( P = 7.5 \text{ s}, \dot{P} = 2.6 \times 10^{-3} \text{s/yr}^{-1} \), yielding \( B = 8 \times 10^{14} \text{ G} \), in remarkable agreement with the predictions by Usov.

Following Usov, we take for the electric field the expression of Goldreich and Julian [9], which at the neutron star surface reads

\[
E \sim R\omega B/c
\]

where \( R \sim 10^6 \text{ cm} \) is the neutron star radius. Taking as reference values for the magnetic field and the period \( 10^{15} \text{ G} \) and 1 ms respectively (note that these values are a little bit less extreme than those used by Usov), the condition for pair creation (eq. [2]) becomes

\[
B_{15} \dot{P}_{-1} > 1
\]

which formally may be satisfied in an object like SRG 1806-20 if it was born with a short period. However, there are good reasons to suspect that \( E \) can never reach \( E_c \), because competing processes tend to damp the field. Pair production by photon splitting in a magnetic field (the \( 1-\gamma \) pair production) is expected to be extremely effective in magnetars. This process was first considered by Sturrock [10] in the context of pulsar electrodynamics and has a threshold

\[
B_p E_\gamma \sim 4 \times 10^{18} \text{ eV G}
\]

where \( E_\gamma \) is the photon energy and \( B_p \) is the perpendicular component of the magnetic field. So, \( \gamma \)-rays of energies about \( 10^7\text{ eV} \) moving in magnetic field \( \sim 10^{12} \text{ G} \) will produce \( e^+ - e^- \) pairs. The pair cascade is sustained by synchrotron (curvature) photons and \( 1-\gamma \) pair production. This in Sturrock’s scenario produces sparks in the electroactive gap. Though the process in a way is a sort of vacuum breakdown, it is largely mediated by the magnetic field. The sparking inhibits the growth of the \( E \)-field well below \( E_c \). We note, however, that recent observations of highly magnetized radio pulsars with \( B > 4 \times 10^{13} \text{ G} \) [11], support the idea of Usov and Melrose [12], that photon splitting is inhibited.
by polarization selection rules, so the idea that $1 - \gamma$ process are more important than vacuum breakdown should be taken with care.

Another astrophysical scenario, which can be relevant for the present discussion, is the coalescence of binary neutron stars. This is nowadays a popular scenario for producing GRBs at cosmological distances and was first suggested by Blinnikov et al. [13]. In this case the electric field is generated by the fast orbital motion of the magnetized neutron stars as they spiral in, much in the same way as the rotating dipole produce the $E$-field in an isolated neutron star (see eq. [3]). This possibility was considered by Vietri [14] (see also [15]), who found that large electric fields may indeed form

\[ E \sim \frac{v}{c}B \sim 5 \cdot 10^{14} \left( \frac{R}{10^6 \text{ cm}} \right)^{-7/2} \left( \frac{B}{10^{15} \text{ G}} \right) \text{ statvolt cm}^{-1}. \] (6)

where the two neutron stars are assumed to be nearly in contact (typical separation $\sim R$, the star radius) and moving at Keplerian velocities.

Ruffini and Treves [16] proposed that a neutron star, rotating in vacuo should be endowed with a net charge, as it follows from a variational principle. For short periods the electric field has a form very similar to that of eq. (3). If this is the case, the same considerations on VB presented earlier in this section should apply.

High electric fields can be also generated when the inner edge of a Keplerian accretion disk rotates faster than the neutron star [17]. Also in this case $E \sim B$ and all the above discussion is again valid, but in realistic astrophysical situations, like X-ray binaries, the field turns out $\sim 10^9$ statvolt cm$^{-1}$, too low for producing VB.

3. – Accreting Black Holes

We assume, as in the case of pulsars, that the electric field is the Lorentz transformation of the $B$-field. However it is much harder to associate a huge $B$-field to a black hole (BH) than to a neutron star.

A rather sound scenario is that of taking an accreting BH and considering the compression of the $B$-field entangled in the infalling material. Accretion compresses the $B$-field, and if the flux is conserved, the field is amplified. Here we give a quasi-Newtonian description and take spherical symmetry (see e.g. [18]). The maximum field is generally taken to be of the equipartition value,

\[ B \sim U_G \sim \frac{\dot{M}}{4\pi r^2 v} \frac{GM}{r}, \] (7)

where $v$ is the infall velocity and $\dot{M}$ the accretion rate. At $r \sim r_G = 2GM/c^2$, $v \sim c$ and one has

\[ B \sim \left( \frac{2Mc}{r_G^2} \right)^{1/2} \sim 5 \times 10^8 \xi^{1/2} \left( \frac{M}{M_\odot} \right)^{-1/2}. \] (8)

where $\xi$ is the accretion rate in units of the Eddington rate $\dot{M}_E = 4\pi Gm_p M/\sigma_T c$. Assuming again $E \sim B$ the VB condition becomes
In steady state $\xi$ is essentially the inverse of the efficiency. Even in the case of a solar mass BH, accretion should be $\sim 10^{12}$ larger than the Eddington rate in order to enter the VB regime. Note that eq. (9) indicates that the more massive the BH is, the more difficult is to fulfill eq. (2). Suppose that $\xi$ could be taken arbitrarily large. Very high accretion rates can be reached if neutrino losses dominate: the “Eddington” rate for neutrino losses is in fact much larger than that associated to photons. Still, as in the case of pulsars, since the electric field is due to a huge $B$-field, synchrotron-$1 - \gamma$ pair production showers will quench the $E$-field below the critical value.

4. – Charge separation by a flash of radiation

Here we focus on the $E$-field produced by the charge separation induced on a globally neutral plasma by a strong radiation field. The basic idea is that the radiative force on electrons is a factor $\sim (m_e/m_p)^2$, the ratio of the Thomson cross-sections, larger than on ions. Schwartsman [19] considered a spherical accretion model, showing that in order that the electron and ion to fall in at the same speed, the central body must acquire a positive charge. Michel [20] extended the treatment to the case of an accreting BH. Maraschi et al. [21] studied the flow and the $E$-field for luminosities approaching the Eddington limit, $L_E$. More recently this problem was reconsidered by Turolla et al [22], who in particular examined its efficiency to accelerate positrons (the Schwartsman accelerator). In [23] it was discussed under which condition the $E$-field may reach the breakdown value within stationary models. Supposing that $L \sim L_E$ the only free parameter is the mass of the accreting BH. VB is possible only for $M \leq 10^{20}$ g, a value which makes dubious the astrophysical relevance of the mechanism.

The main restriction of the previous treatment is the stationarity hypothesis, which limits the luminosity to $L_E$. Here we overcome this restriction, and explore the conditions for which a burst of radiation of arbitrary luminosity may induce an $E$-field at the VB level.

Consider a spherical shell of hydrogen plasma, and let it be transparent to radiation, which is characterized by luminosity $L$. Let the electron-photon cross section be the Thomson one, $\sigma_T = 0.66 \times 10^{-24}$ cm$^2$. The charge separation induced by the radiation produces, at distance $r$, an electric field of intensity [19, 22]:

$$E = \frac{\sigma_T L}{4\pi c r^2}. \quad (10)$$

Note that eq. (10) should be regarded only as an estimate of the electric field, since a non-stationary situation is considered. Note also that in the present picture the electric field is not in vacuo, but in a plasma, charge-separated by the photons. As an order of magnitude we still take equation (1) as valid to estimate the VB condition.

Combining equations (1) and (10) we obtain the critical luminosity which should induce VB.
Having in mind models of GRBs, we scale the size of the emitting region to $10^6$ cm, so the above equation becomes

$$L_c = 4 \times 10^{51} r_6^2 \text{erg s}^{-1}. \quad (12)$$

This typical value of the luminosity is of the same order of that of GRBs.

By introducing the “vacuum breakdown” parameter

$$l_c = \frac{L}{L_c} = \frac{\sigma_T \lambda_c L}{8 \pi r^2 m_e c^3} \quad (13)$$

it is apparent that $l_c$ is related to the well-known “compactness parameter”, $l = L \sigma_T / 4 \pi r m_e c^2$ [24], which measures the opacity of a source to photon-photon interaction. In fact one has

$$l_c \sim 5 \times 10^{-16} l r_6^{-1} \quad (14)$$

which implies that a source in “breakdown” condition (i.e. with $l_c \sim 1$) is also extremely compact, $l \gg 1$. A lower limit to the photon energy density under VB conditions is simply

$$U = \frac{L_c}{4 \pi r^2 c} \sim \frac{2 m_e c^3}{\sigma_T \lambda_c} \sim 10^{28} \text{erg cm}^{-3}. \quad (15)$$

If the photon spectrum is a blackbody, one can obtain a lower limit to the typical photon energy

$$E_\gamma \sim \left(\frac{U}{a}\right)^{1/4} \sim 3 \text{MeV}. \quad (16)$$

Note that this limit is independent of the source size $r$.

5. Conclusions

Present models of GRBs indicate that photon fluxes leading to the VB condition $l_c \geq 1$ may be achieved. This corresponds to a huge compactness parameter (see eq. [14]). If the spectrum is not far from a blackbody, equation (16) shows that photon-photon interaction will produce a plethora of pairs.

Although in principle the photon energies may be less than the value implied by eq. (16), remaining below the threshold of pair creation, the situation may be considered in a “gedanken experiment”, but it seems to us very unlikely in a realistic astrophysical situation.
Our conclusion is that in GRBs vacuum polarization by electric field produced by an extreme luminosity may occur, but its consequences will be masked by the multitude of pairs produced by photon-photon interaction.

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