

Looking for Light Pseudoscalar Bosons in the Binary Pulsar System J0737-3039

Arnaud Dupays and Carlo Rizzo

Laboratoire Collisions, Agrégats, Réactivité, IRSAMC, CNRS/UPS, 31062 Toulouse, France

Marco Roncadelli

INFN, Sezione di Pavia, Via A. Bassi 6, I-27100 Pavia, Italy

Giovanni F. Bignami

*Centre d'Etude Spatiale des Rayonnements, CNRS/UPS, 31401 Toulouse, France
INFN/IASF, Sezione di Milano, Italy, and Dipartimento di Fisica Nucleare e Teorica,
Università di Pavia, and INFN, Sezione di Pavia, Pavia, Italy*

(Dated: October 12, 2005)

We present numerical calculations of the photon-light-pseudoscalar-boson conversion in the recently discovered binary pulsar system J0737-3039. Light pseudoscalar bosons (LPBs) oscillate into photons in the presence of strong magnetic fields. In the context of this binary pulsar system, this phenomenon attenuates the light beam emitted by one of the pulsars, when the light ray goes through the magnetosphere of the companion pulsar. We show that such an effect is observable in the gamma-ray band since the binary pulsar is seen almost edge-on, depending on the value of the LPB mass and on the strength of its two-photon coupling. Our results are surprising in that they show a very sharp and significant (up to 50%) transition probability in the gamma-ray ($>$ tens of MeV) domain. The observations can be performed by the upcoming NASA GLAST mission.

Light pseudoscalar bosons (LPBs) coupled to two photons have attracted considerable interest in the last few years and their implications for elementary-particle phenomenology, astrophysics and cosmology have been thoroughly investigated [1, 2, 3]. Specifically, the LPB mass m is assumed to be $m < 1$ eV and the LPB-photon-photon coupling is described by the interaction lagrangian

$$\mathcal{L}_{int} = -\frac{1}{4M} F^{\mu\nu} \tilde{F}_{\mu\nu} \phi = \frac{1}{M} \mathbf{E} \cdot \mathbf{B} \phi, \quad (1)$$

where ϕ denotes the LPB field, $F^{\mu\nu}$ is the usual electromagnetic field strength ($\tilde{F}_{\mu\nu}$ is its dual), and M is the inverse coupling constant with the dimension of a mass. Natural Lorentz-Heaviside units with $\hbar = c = 1$ are employed throughout.

Because the mass eigenstates of the LPB-photon system differ from the corresponding interaction eigenstates, interconversion takes place, a phenomenon quite similar in nature to flavour oscillations for massive neutrinos. However, since the off-diagonal term (1) involves “two photons”, one of them actually corresponds to an external field. So, photon-LPB oscillations occur only in the presence of external electric or magnetic fields.

A particular case of LPB is the standard *axion*, namely the pseudo-Goldstone boson associated with the Peccei-Quinn $U(1)$ global symmetry invented to solve the strong CP problem [4]. Although the exact value of the axion mass m is model-dependent, generally one finds $m \simeq 0.7 (10^{10} \text{ GeV}/M) \text{ eV}$. Besides providing a natural candidate for nonbaryonic dark matter [5], the standard axion can in principle be detected with high-precision laboratory experiments thanks to its two-photon coupling in eq. (1). In this connection, two strategies have been pro-

posed. One is based on the resonant axion-photon conversion inside a tunable microwave cavity [6], while the other relies upon the induced ellipticity and change of polarization plane of an initially linearly-polarized laser beam [7]. In either case, a strong external magnetic field must be present. Generic LPBs with a two-photon coupling (1) can also be discovered in this way, provided of course that their mass m and inverse coupling constant M fall into suitable ranges which depend on the experimental arrangement.

Quite recently, using an experimental setup based on ref. [7], the PVLAS collaboration has observed an unexplained effect that can be interpreted in terms of photon oscillations into a LPB with mass $m \simeq 1.0 \cdot 10^{-3} \text{ eV}$ and inverse coupling constant $M \simeq 3.8 \cdot 10^5 \text{ GeV}$ [8]. Clearly these values prevent the LPB in question to be the standard axion.

On the other hand, LPBs are copiously produced in the core of stars, owing again to the two-photon coupling (1). Therefore, under the assumption that LPBs escape from stars, energy-loss arguments put strong bounds on M . Typically, one gets $M > 10^{10} \text{ GeV}$ [2]. This conclusion is further supported by the result of the CAST experiment [3]. Manifestly, the PVLAS result contradicts this bound by about five orders of magnitude. A possible way out of this difficulty is to suppose that, because of some new physics, the LPB detected by PVLAS is trapped inside star cores. A specific scenario in which this indeed occurs has been put forward [9]. While no fully satisfactory solution to this problem has yet been found, the existence of new physics at low energy is evidently called for, and this poses an exciting challenge for contemporary research. Thus, the need for an independent test of

the PVLAS result looks imperative.

In this Letter, we show that LPBs can give rise to observable effects if suitably selected binary pulsars are monitored in the gamma-ray band with future satellite-borne detectors like GLAST. Our analysis is carried out for arbitrary values of m and M , and the requirement of observability defines the corresponding parameter ranges. It turns out that the values found by PVLAS fall within these ranges, and so our result provides a cross-check for the PVLAS claim of a new LPB. Actually, our calculations apply also to the case of scalar bosons, except that the $\mathbf{E} \cdot \mathbf{B}$ coupling should be replaced by the $\mathbf{E} \cdot \mathbf{E} - \mathbf{B} \cdot \mathbf{B}$ coupling.

In what follows we will focus, as a model system, on the specific case of the recently-discovered binary pulsar system J0737-3039 which is seen almost edge on [10] and for which gravitational microlensing has also been studied [12]. We have already shown [13] that in the peculiar geometry of this system it will be possible to observe quantum vacuum lensing resulting from the photon-magnetic field interaction, with photon energies in the X-ray domain. There we used the same system, again starting with the photon beam from one of two stars (pulsar A). Denote by ρ the impact parameter of the beam, namely its projected distance from the companion, pulsar B . When ρ is small, the beam goes through the magnetosphere of pulsar B . Therefore the observed photons traverse a region where a strong magnetic field is present. Assume now that a LPB exists. Then, owing to its two-photon coupling (1), some of the photons will be converted into LPBs, thereby decreasing the beam intensity. Depending on the actual values of the physical parameters involved, the beam attenuation can be substantial. As we will see, the effect turns out to be important for photons with energy larger than 10 MeV, namely in the gamma-ray band. Remarkably enough, these photons propagate totally unimpeded in the magnetosphere of pulsar B , and so we do not have to bother about further potential sources of beam attenuation. Moreover, the effect under consideration does not depend on any new physics responsible for the confinement of the LPBs in the star interiors [9].

The model system studied, J0737 – 3039, is particularly well suited for our purposes. Its orbital plane has currently an inclination angle $i \simeq 87^\circ$ [10], and the orbital precession of the system allows us to predict that the value $i \simeq 90^\circ$ could be achieved before 2020. The orbital period is 2 hours and 45 minutes, while the spinning period of pulsar B is 2.77 seconds. Although the current minimum value of the impact parameter of the light beam from pulsar A is somewhat uncertain, a realistic estimate yields $\rho \simeq 4 \cdot 10^3$ km [11] and this is the value used in our analysis. The geometry of the binary pulsar under consideration is depicted in Fig. (1).

The light beam from pulsar A propagates along the z direction and passes pulsar B at impact parameter ρ .

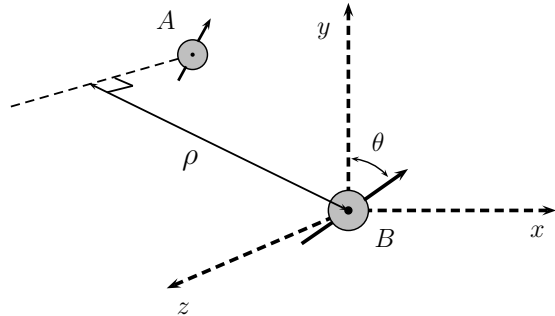


FIG. 1: Geometry of the model binary pulsar system

We introduce a (x, y, z) coordinate system fixed with pulsar B . For simplicity, we suppose that the rotation axis of pulsar B lies along the y direction and that its magnetic dipole moment precedes at an angle $\theta = 45^\circ$ about the y axis. The light beam from pulsar A experiences a time-dependent and inhomogeneous dipolar magnetic field \mathbf{B} . The photon-LPB oscillations are described by the coupled Klein-Gordon and Maxwell equations dictated by lagrangian (1), plus free-field terms. In the short-wavelength approximation (to be justified later), the propagation equations take the following first-order form [14]

$$i \frac{\partial}{\partial z} |\psi(z)\rangle = \mathcal{M} |\psi(z)\rangle, \quad (2)$$

with

$$|\psi(z)\rangle \equiv c_x(z) |x\rangle + c_y(z) |y\rangle + c_\phi |\phi\rangle, \quad (3)$$

where $|x\rangle$ and $|y\rangle$ are the two linear polarization states of the photon (propagating in the z -direction) along the x and y axis, respectively, and $|\phi\rangle$ is the LPB state. Moreover, the mixing matrix \mathcal{M} is given by

$$\mathcal{M} = \begin{pmatrix} \omega + \Delta_{xx} & \Delta_{xy} & B_x/2M \\ \Delta_{yx} & \omega + \Delta_{yy} & B_y/2M \\ B_x/2M & B_y/2M & \omega - m^2/2\omega \end{pmatrix}, \quad (4)$$

with ω denoting the photon/LPB energy. While the terms appearing in the third row and column of \mathcal{M} have an evident physical meaning, the Δ -terms require further discussion. Generally speaking, they reflect both the properties of the medium and the QED vacuum polarization effects. Off-diagonal terms Δ_{xy}, Δ_{yx} directly mix the photon polarization states and typically give rise to Faraday rotation. Clearly they are important when the polarization of photon beam is taken into account, but become irrelevant for the present analysis. The diagonal elements Δ_{xx}, Δ_{yy} arise from two independent contributions: vacuum polarization effects and plasma effects. The first ones are due to one-loop Feynman diagrams and

are analytically described by the Heisenberg-Euler effective lagrangian when terms involving LPBs in the loops are discarded, as is currently done. Neglecting again beam polarization effects, we get $\Delta_{xx}^{QED} \simeq \Delta_{yy}^{QED} \simeq (\alpha/45\pi)(B/B_{cr})^2 \omega$, where α is the fine-structure constant and $B_{cr} \simeq 4.41 \cdot 10^{13}$ G denotes the critical magnetic field [15]. Plasma effects arise from the presence of free charges in the magnetosphere of pulsar B and their contribution is $\Delta_{xx}^{PL} \simeq \Delta_{yy}^{PL} \simeq -2\pi\alpha n_e/\omega m_e$, where m_e is the electron mass and n_e is the electron density [14]. Off-diagonal QED effects and plasma effects turn out to be presently irrelevant and will be neglected (more about this, later).

We solve eq. (2) numerically in the equivalent exponential form

$$|\psi(z)\rangle = \mathcal{T} \exp\left(-i \int_{z_0}^z \mathcal{M}(z') dz'\right) |\psi(z_0)\rangle, \quad (5)$$

where \mathcal{T} is Dyson's ordering operator. Since the \mathcal{M} matrix is explicitly z -dependent, the propagation is computed iteratively, i.e. in steps of small intervals δz . For small enough δz , the \mathcal{M} matrix can be considered as constant over one distance step, and the short-propagation iterations can be calculated as [16]

$$|\psi(z + \delta z)\rangle \simeq \exp(-i\mathcal{M}(z)\delta z) |\psi(z)\rangle. \quad (6)$$

The propagation is performed from z_0 to z_{max} with the initial condition corresponding to a pure photon state. Here z_0 is fixed by the trajectory of pulsar A and z_{max} is chosen so that $B_x(z)/2M \simeq B_y(z)/2M \simeq 0$ for $z > z_{max}$. The transition probability is then

$$P_{(\gamma_j \rightarrow \phi)} = |\langle \phi | \psi(z_{max}) \rangle|^2 = |c_\phi(z_{max})|^2, \quad (7)$$

where $j = x$ (resp. y) refers to the initial photon polarization along the x -axis (resp. y -axis). For an unpolarized photon beam, the transition probability is

$$P_{(\gamma \rightarrow \phi)} = \frac{P_{(\gamma_x \rightarrow \phi)}}{2} + \frac{P_{(\gamma_y \rightarrow \phi)}}{2}. \quad (8)$$

In what follows we use the values of m and M as suggested by the PVLAS result. In Fig. 2, we have plotted the transition probability $P_{(\gamma \rightarrow \phi)}$ versus the photon energy ω , for a gamma beam with impact parameter $\rho = 4 \cdot 10^3$ km.

The strong energy-dependence exhibited by $P_{(\gamma \rightarrow \phi)}$ suggests to investigate the photon-LPB conversion in the region of the broad maximum, namely for $\omega > 10$ MeV. Observe that this circumstance fully justifies the above short-wavelength approximation.

Actually, the threshold behaviour of $P_{(\gamma \rightarrow \phi)}$ can be understood as follows. Consider a drastically simplified situation in which the magnetic field experienced by the light beam is stationary and homogeneous. A typical value of the magnetic field strength on the surface of a neutron star, namely at a distance $r \simeq 10$ km

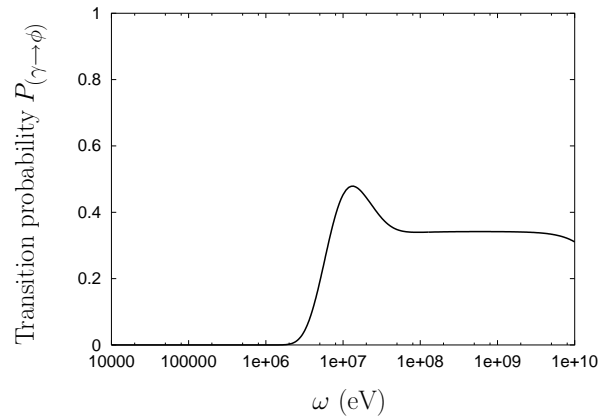


FIG. 2: Transition probability versus photon energy for a trajectory of the light beam with an impact parameter $\rho = 4 \cdot 10^3$ km.

from the centre, is $B_0 \simeq 10^{12}$ G. Since \mathbf{B} is dipolar, it goes like $\sim r^{-3}$, and so the magnetic field strength at $\rho \simeq 4 \cdot 10^3$ km is $B \simeq 1.6 \cdot 10^4$ G. Correspondingly, we have $\Delta_{xx}^{QED} \simeq \Delta_{yy}^{QED} \simeq 6.3 \cdot 10^{-18} (\omega/\text{MeV})$ eV. Because the terms Δ_{xy}, Δ_{yx} presently get only a QED contribution, they should not exceed $\Delta_{xx}^{QED} \simeq \Delta_{yy}^{QED}$. Following ref. [14], it is straightforward to see that the terms $\Delta_{xx}^{PL} \simeq \Delta_{yy}^{PL}$ are much smaller than $\Delta_{xx}^{QED} \simeq \Delta_{yy}^{QED}$ for $B \simeq 1.6 \cdot 10^4$ G. We find $B_x/2M \simeq B_y/2M \simeq 0.4 \cdot 10^{-12}$ eV and $m^2/2\omega \simeq 0.5 \cdot 10^{-12} (\text{MeV}/\omega)$ eV. Correspondingly Δ_{xy} and Δ_{yx} turn out to be the smallest elements of \mathcal{M} . Thus, we see that off-diagonal QED effects as well as plasma effects are indeed negligible (in agreement with previous assumptions). In addition, mixing effects in \mathcal{M} should become physically important when the ratio of the off-diagonal elements to the difference of the diagonal ones starts to be of order 1. Therefore, photon-LPB conversion is expected to actually occur for $\omega > 1$ MeV, which means that a substantial beam attenuation ought to show up when gamma-ray photons above 10 MeV are observed.

It makes even more sense, at this point, to consider the case of J0737, because pulsars are frequently celestial gamma-ray sources [17], because of the very special geometry of this system and because the NASA GLAST mission (due to launch in 2007) will have a pulsar gamma-ray detection sensitivity up to two orders of magnitude better than any previous telescope [18].

Assuming that the gamma photon beam emitted by pulsar A is not polarized, the temporal behaviour of the considered effect is best expressed in terms of the total transmission $A = 1 - P_{(\gamma \rightarrow \phi)}$ of the gamma ray after propagation in the magnetosphere of pulsar B . In Fig. 3, we plot A versus time as pulsar A moves in its nearly edge-on orbit. Our numerical simulation predicts in this case a strong attenuation of the photon beam up to 50 %

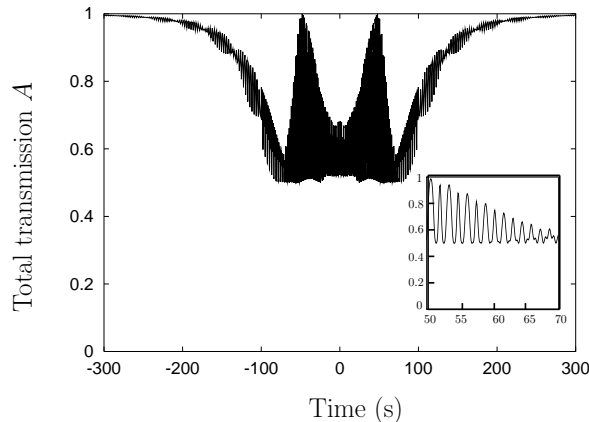


FIG. 3: Total transmission of the gamma photon beam emitted by pulsar A versus time. Inset shows the modulation mainly due to the rotation of the magnetic dipole moment of pulsar B .

with a time duration of about 200 s. The effect has three different temporal structures. Of course, the broad minimum, from -200 s to $+200$ s, corresponds to the transit of pulsar B "in front" of pulsar A . The tens-of-seconds, symmetric peaks are due to photon-LPB oscillations depending on the path through the interaction region with pulsar B . Finally, the highest frequency modulation, shown in inset, is due to the rotation of the magnetic dipole moment of pulsar B . Under the assumptions corresponding to the PVLAS result, a macroscopic effect could be observable from the J0737-3039 system, given enough instrumental sensibility and observing time. We note that pulsar A also generates a similar effect on the gamma photon beam emitted by pulsar B . Since the spin period of pulsar A is smaller than the one of pulsar B (23 ms), the modulation period of the effect will be also smaller.

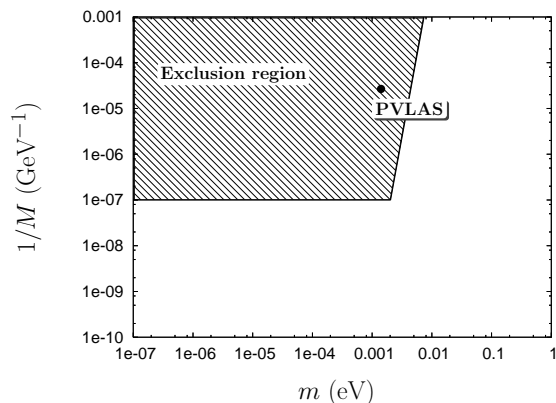


FIG. 4: Exclusion region in the case that the existence of the attenuation is excluded at 10% level.

Finally, Fig. 4 shows the region in the $m - M$ parameter space which is excluded by no detection of an attenuation A at the 10% level. To get such an attenuation, one needs to count 100 photons during the total integrating time. For two weeks observation time, this corresponds to a flux from pulsar A of about $2 \cdot 10^{-7}$ photons/cm²/s which is a reasonable flux according to previous observations of several pulsars [17]. We note in any case that the GLAST sensibility curves allow for a much weaker minimum detectable flux, down to $1 \cdot 10^{-10}$ photons/cm²/s [19]. In conclusion, we have shown that LPBs can produce observable effects in a binary pulsar system seen almost edge-on, like J0737-3039. The effect is in the gamma-ray band, depending of course on the actual values of the parameters m and M . This is an intriguing feature of our result, since pulsars are frequently celestial gamma-ray sources and the NASA GLAST mission (due to launch in 2007) will have a pulsar gamma-ray detection sensitivity up to two orders of magnitude better than any previous telescope [18]. Of course, new binary pulsar systems will be discovered soon through radio-astronomy or possibly by the very GLAST mission. A potentially useful new tool seems to be coming of age.

-
- [1] G. G. Raffelt, *Stars as Laboratories for Fundamental Physics*, (University of Chicago Press, Chicago, 1996). E. Masso and R. Toldra, Phys. Rev. D **52** 1755 (1995). E. Masso and R. Toldra, Phys. Rev. D **55** 7967 (1997).
 - [2] G. G. Raffelt, hep-ph/0504152 (2005).
 - [3] K. Zioutas *et al.*, Phys. Rev. Lett. **94**, 121301 (2005).
 - [4] J. H. Kim, Phys. Rep. **150**, 1 (1987). H. Y. Cheng, **158**, 1 (1988).
 - [5] M. S. Turner, Phys. Rep. **197**, 67 (1990). G. G. Raffelt, Phys. Rep. **198**, 1 (1990).
 - [6] R. Bradley *et al.*, Rev. Mod. Phys. **75**, 777 (2003).
 - [7] L. Maiani, R. Petronzio and E. Zavattini, Phys. Lett. B **175**, 359 (1986).
 - [8] E. Zavattini *et al.*, arXiv:hep-ex/0507107v1, (2005), (submitted to PRL).
 - [9] E. Masso and J. Redondo, astro-ph/0504202 (2005).
 - [10] M. Burgay *et al.*, Nature **426**, 531 (2003).
 - [11] W. A. Coles *et al.*, astro-ph/0409204 (2004).
 - [12] D. Lai and R. R. Rafikov, Astrophys. J. **621**, L41 (2005).
 - [13] A. Dupays, C. Robillard, C. Rizzo and G. F. Bignami, Phys. Rev. Lett. **94**, 161101 (2005).
 - [14] G. Raffelt and L. Stodolsky, Phys. Rev. D **37**, 1237 (1988).
 - [15] S. L. Adler, Ann. Phys. (N.Y.) **67**, 599 (1971).
 - [16] W. Heather, Comp. Phys. Comm. **63**, 691 (1991).
 - [17] G. F. Bignami and P. A. Caraveo, Annu. Rev. Astron. Astrophys. **34**, 331-81 (1996).
 - [18] D. J. Thomson, IAU Symposium, astro-ph/0310509 (2004).
 - [19] See GLAST LAT Performance, <http://www-glast.slac.stanford.edu>