Phonon-Axion-Like Particle Coupling Constant and Cosmological Observations.

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May 26, 2008

Abstract

We estimated the photon-pseudoscalar particle mixing constant from the effect of cosmological alignment and cosmological rotation of polarization plane of distant QSOs, revealed by Hutsemekers et al. [1]. This effect is explained in terms of birefringent phenomenon due to photon-pseudoscalar (axion-like) particle mixing in a cosmic magnetic field.

On the contrary, one can estimate the strength of the cosmic magnetic field using the constraints on the photon-axion-like particle coupling constant from the CAST experiment and from SNe Ia dimming effect [2]. In a result, the lower limit on the intergalactic (z ≈ 1 ÷ 2) magnetic field appears at the level of about 4 × 10^{-10} ÷ 10^{-11} G.

Keywords: cosmological magnetic field, axion, quasar, polarization.

1 Introduction

One of the most intrigue recent astronomical discoveries was detecting extreme-scale alignments of quasar polarization vectors by Hutsemekers et al. [1, 3]. Based on sample of 355 quasars with significant optical polarization and using various statistical methods, they revealed that quasar polarization vectors are not randomly oriented over the sky as it could expected. The probability of this effect is often in excess of 99.9%. The polarization vectors appear coherently oriented over huge (∼ 1Gpc) cosmological regions of the sky located at both low (z ∼ 0.5) and high (z ∼ 1.5) redshifts and characterized by strongly different preferred directions of quasar polarization. Two possible interpretations of this effect have been proposed. The first one is a weakly developed interpretation like a global rotation. But the properties that Hutsemekers et al. [1] observed correspond qualitatively better to the dichroism and birefringence produced by photon-pseudoscalar oscillation within the intergalactic magnetic field [4].

In order to further study the reality of this alignment effect, Hutsemekers et al. [1] have subsequently carried out another test which consisted in obtaining new polarimetric measurements located in a region of the sky where the first preliminary result of the alignment were revealed. These new measurements independently confirmed the existence of coherent orientations of quasar polarization vectors in the considered regions of sky. Another exciting result obtained by Hutsemekers et al. [1] is that the alignment effect seems to be close to an axis not far from preferred directions tentatively identified in the CMB maps. These conclusions have been made at the base as of new polarization observation of a new sample of 335 polarized quasars with accurate linear polarization measurements, so of combined recent data from the literature. The most part of the polarimetric observations were carried out at the European Southern Observatory (Chile).

Although the interpretation of the alignment effect remains uncertain, the effect itself appear as new way to test the Universe and dark energy and dark matter components at large scale. This effect presents also possibility to investigate the physical properties of Intergalactic Medium (IGM). The last interesting result has been recently presented by Borguet et al. [5]. They found that the orientation of the rest-frame UV/blue extended emission is correlated to the direction of the quasar polarization and this effect may be connected with Type 1/Type 2 dichotomy of QSO host galaxies.

The final conclusion made by Hutsemekers et al. [1] is that quasar polarization angles are definitely not random oriented over the sky. Polarization vectors appear coherently oriented over very large spatial

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scales in regions located at both low and high redshifts and characterized by different preferred directions. Authors claimed that polarization vector alignment seems connected on a sizeable fraction of the known Universe points towards a global mechanism acting at the scale of the Universe. They noted also that the observed behaviour quite well corresponds to the dichroism and birefringence predicted by photon-pseudoscalar oscillation within an intergalactic magnetic field. If it is right then we might have found a signature of either dark matter or dark energy.

One should mention that the linear dichroism of aligned interstellar dust grains in our Galaxy produces also linear polarization along the line of sight. This polarization can contaminate to some extent the quasar measured data and this may change their position angles. However Sluse et al. [6] investigated carefully this effect and showed that interstellar polarization has a little effect on the polarization angle distribution of significantly polarized ($p_t \geq 0.6\%$) quasars.

From the point of view photon-pseudoscalar (ultra light axion or axion-like pseudoscalar particle) mixing in a magnetic field seems as a quite promising interpretation (see [7, 8, 9, 10, 4]) especially because many of the observed properties of the alignment effect were qualitatively predicted. The last PVLAS Collaboration experiment reported the upper limit of observation of a laser light polarization rotation in vacuum in the presence of a transverse magnetic field is increasing the interest to this phenomenon and to search of its astrophysical manifestations ([11, 4]).

Here we estimate the value of the constant coupling of photon-pseudoscalar mixing from the data of the cosmological rotational polarization plane of the intrinsic polarization of QSOs in the intergalactic magnetic field (IGMF).

## 2 Photon-pseudoscalar mixing and birefringent effect in a magnetic field: the basic equations

The probability of the magnetic conversion of photons into low-mass pseudoscalar (scalar) particles were calculated by Raffelt and Stodolsky [12] (see also [13]). The case of massless pseudoscalars (arions) was developed by Anselm and Uraltsev [14] (see also [15, 8]).

The expression for this probability takes a form:

$$P(\gamma_\parallel \leftrightarrow a) = \frac{1}{1 + x^2} \sin^2 \left( \frac{1}{2} B_\perp g_{a\gamma} L \sqrt{1 + x^2} \right)$$  \[(1)\]

where

$$x = \frac{(\varepsilon - 1)\omega}{2B_\perp g_{a\gamma}}$$  \[(2)\]

$\omega$ is the radiation frequency, $\varepsilon$ is the dielectric function of a medium that the light is propagating through, $B_\perp$ is the magnetic field component perpendicular to the photon direction, $g_{a\gamma}$ is the coupling constant between photons and pseudoscalars.

The essential features of this probability functions are: (a) its oscillatory character, and (b) the fact that the conversion process is very sensitive to the polarization state of photon. The last fact means that only a single polarization state with the electric vector oscillating into the plane of directions of the magnetic field and the photon propagation is subject to the conversion.

The conversion process depends strongly on the dielectric function of a medium. Assuming that the medium is a plasma with an electron density $N_e$ and a neutral gas (for example, hydrogen) with density $N_H$, we find:

$$1 - \varepsilon = \frac{\omega^2}{\omega_p^2} - 4\pi\beta N_H - \frac{28\alpha^2}{45m_\epsilon^2} B^2 - \frac{m_a^2}{\omega^2}$$  \[(3)\]

The $\omega_p$ presents the most common expression for the dielectric function, including the plasma polarizability (the first term) and the contribution of a neutral gas ($\beta$ is the atomic polarizability). The third term describes the contribution of polarizability of a vacuum in a magnetic field. The last term takes into account the contribution of the scalar field describing the pseudoscalar particle. For the massless bosons (arions) it equals to zero.
In Eqs. (1-3) we use the Lorentz-Heaviside system of units with \( \hbar = c = 1 \) and a fine structure constant \( \alpha = e^2/4\pi = 1/137 \). In this system of units one gauss corresponds to \( 6.9 \times 10^{-2}(eV)^2 \) and 1 cm corresponds to \( 5 \times 10^4(eV)^{-1} \).

Photon-pseudoscalar mixing also yields birefringent effect in a magnetic field because the change of parallel polarization mode is produced via the conversion process of photons into pseudoscalars. Therefore the plane of polarization will be oscillated and ellipticity will be acquired by a linear polarized beam propagating across magnetic field lines in vacuum. In a result one can present the following expression for rotation angle \( \theta \) for a homogeneous case:

\[
\tan \theta(L) = \frac{1}{2(1 + x^2)} \sin^2 \left( \frac{1}{2} B_{\perp} g_{a\gamma} L \sqrt{1 + x^2} \right) \tag{4}
\]

For a pure vacuum and the weak mixing the (4) transforms to:

\[
\theta(L) = \frac{1}{8} g_{a\gamma} B_{\perp}^2 L^2 \tag{5}
\]

Later on, we are using (5), but are taking into account the dependence of the basic physical parameters on the cosmological redshift \( z \).

For a cosmologically distant source the change in polarization angle \( \Delta\theta \) due to propagation through intergalactic medium with a magnetic field can be presented as:

\[
\Delta\theta(z) \approx \frac{1}{8} \left( g_{a\gamma} \int_{z_0}^{z_1} B_{\perp}(z) \frac{dL}{dz} \right)^2 \tag{6}
\]

\[
L(z) = \frac{c}{H(z)} = \frac{c}{H_0} \int_0^z \frac{dz}{(\Omega_m (1 + z)^3 + \Omega_\Lambda)^{1/2}} \tag{7}
\]

We use the standard cosmological model: \( \Omega_m = 0.27 \), \( \Omega_\Lambda = 0.73 \) and \( H_0 = 75 km/sMpc \). We consider the situation when the light beam is propagating in the IGM (InterGalactic Medium) through the cosmological distance \( \Delta z = z_1 - z_0 \). In the special case, one can consider the situation when \( z_0 = 0 \). But here we shall consider the situation presented by Hutsemekers et al. \( \text{II} \), namely, \( z_0 = 0.5 \), \( z_1 = 1.5 \) and \( z_0 = 1 \), \( z_1 = 2 \). The typical value of the rotation angle obtained by Hutsemekers et al. \( \text{II} \) from the polarimetric observations of quasars was to be \( \Delta\theta \approx 0.5 (\Delta\theta \approx 30^{\circ}) \) for the examined redshifts \( z_0 \) and \( z_1 \).

Let us remind also that we consider the polarization rotation effect due to the process of magnetic conversion of a photon into a pseudoscalar particle. In our case unlike on the Faraday rotation effect there is no strong dependence of a rotation angle on the light wavelength. The absence of such kind dependence means that the oscillation length via the photon conversion process is less compare to other physical oscillation lengths and corresponds to characteristic scale of the intergalactic magnetic field. The numerical estimates will be presented in the next sections.

## 3 Magnetic photon conversion in the IGM

The Eqs. (5-7) are acting if the coherence length \( L_B \) in the IGM is determined by the magnetic field strength. It means that the coherence lengths connected with plasma oscillation frequency and pseudoscalar mass must be essentially higher than \( L_B \). It derives the following relations:

\[
L_B = \frac{\pi}{g_{a\gamma} B} \ll L_p = \frac{\pi \omega}{\omega_p^2}, \quad L_B \ll L_m = \frac{\pi \omega}{m_a^2} \tag{8}
\]

where \( \omega_p \) is the plasma frequency in IGM and \( m_a \) is the mass of a pseudoscalar (axion-like) particle.

The basic problem for the solution of (5) is to find the dependence of the intergalactic magnetic field on the cosmological redshift, i.e. \( B_{\perp}(z) \).

The first model, that will be tested, is the dependence corresponding to equipartition between magnetic and CMB radiation pressures:

\[
B_{\perp}(z) = B_0 (1 + z)^2 \tag{9}
\]

It should be mentioned that such kind dependence have been determined by Gnedin and Silant’ev \( \text{II} \) for quasar magnetic fields from the observed decrease in the fraction of polarized quasars with increasing
redshift. Their conclusion has been given at the base of observations by Impey et al. [17] and Wills et al. [18].

For the redshift dependence law of [9] we obtain the following estimate of the rotation angle for QSOs lying in the redshift interval of $0.5 \leq z \leq 1.5$:

$$\sqrt{\Delta \theta} = 0.244 \frac{c B_0 \rho_{\gamma}}{H_0 L_{m}} = \left( \frac{g_{\alpha \gamma}}{6 \times 10^{-23} (eV)^{-1}} \right) \left( \frac{B_0}{10^{-9} G} \right)$$  \hspace{1cm} (10)

For the redshift interval $1.0 \leq z \leq 2.0$ we obtain

$$\sqrt{\Delta \theta} = 0.257 \frac{c B_0 \rho_{\gamma}}{H_0 L_{m}} = \left( \frac{g_{\alpha \gamma}}{4 \times 10^{-23} (eV)^{-1}} \right) \left( \frac{B_0}{10^{-9} G} \right)$$  \hspace{1cm} (11)

The next redshift dependence law that will be tested is, so-called, the Chandrasekhar-Fermi law [19]. Their law is based on an interpretation of the dispersion in the observed planes of polarization of the light of the distant objects.

Chandrasekhar and Fermi [19] have suggested the following relation for the magnetic field component projected on the plane of sky perpendicular to the line of sight:

$$B_\bot = \sqrt{\frac{4\pi}{3}} \frac{V_{turb}}{\Delta \theta}$$  \hspace{1cm} (12)

and instead of $V_{turb}$ one uses usually the value of dispersion of observed velocities, i.e. $V_{turb} = \Delta V_{FWHM}$.

For the density of intergalactic medium we use the value of the baryon density of the Universe: $ho = n \Omega_b \rho_{cr}$, where the cosmological parameter $\Omega_b = 0.04$ and the numerical coefficient $n \sim 1$. In a result, the relation (12) transforms to

$$B_\bot = 1.2 \times 10^{-15} (1 + z)^{3/2} \frac{V_{FWHM}}{\Delta \theta}$$  \hspace{1cm} (13)

We use the ratio $\Delta V_{FWHM} = (\sqrt{3}/2)V_{FWHM}$.

To calculate the Eq. (6), we accept the next values of IGM temperature: $T_{IGM} = 10^5 K$. This value is characteristic for warm-hot intergalactic gas and has been obtained from estimates of the ionizing spectral energy distribution as of nearby active galactic nuclei so high-redshift quasars which demonstrate Gunn-Peterson effect [20, 21]. With use the relation $V_{FWHM} \approx V_{thermal}$, we are obtaining from (13) the following expression for the rotation angle ($0.5 \leq z \leq 1.5$):

$$(\Delta \theta)^3 = 10^{-2} \left( \frac{g_{\alpha \gamma}}{10^{-11} GeV^{-1}} \right)^2 \left( \frac{B_0}{10^{-9} G} \right)^2 \left( \frac{75}{H_0} \right)^2 \left( \frac{T_{IGM}}{10^5 K} \right)$$  \hspace{1cm} (14)

Using the rotation angle value $\Delta \theta \approx 0.5$ for $z_0 = 0.5$ and $z_1 = 1.5$ from the data of Hutsemekers et al. [1], we obtain the next constraints for the coupling constant $g_{\alpha \gamma}$:

$$g_{\alpha \gamma} \leq 3.4 \times 10^{-11} GeV^{-1} \left( \frac{10^{-9} G}{B_0} \right) \left( \frac{H_0}{75} \right) \left( \frac{T_{IGM}}{10^5 K} \right)$$  \hspace{1cm} (15)

For intergalactic magnetic field with redshift dependence of [9] we have:

$$g_{\alpha \gamma} \leq 4 \times 10^{-14} GeV^{-1} \left( \frac{10^{-9} G}{B_0} \right) \left( \frac{H_0}{75} \right)$$  \hspace{1cm} (16)

4 Constraints on axion-like particle fundamental parameters

It is evident that in our situation there exists the strong dependence of obtained constraints on the redshift dependence of the intergalactic magnetic field. In a result we obtain the ”soft” upper limit $g_{\alpha \gamma} \leq 3.4 \times 10^{-11} GeV^{-1}$ and the ”hard” upper limit $g_{\alpha \gamma} \leq 4 \times 10^{-14} GeV^{-1}$ of the coupling constant between axion and photon fields.

The next important constraint can be obtained for the mass of a boson (axion-like particle). This constraint can be derived from Eq. (8). This equation requires that the magnetic pseudoscalar-photon mixing coherence length $L_B$ will be less than the coherence length due to the pseudoscalar mass $L_m \sim m_{\alpha}^{-2}$. In a result, we obtain the constraints on the mass magnitude of a pseudoscalar.
The Eqs. (8), (15) and (16) derives:

\[ m_a^2 \ll \omega g_{a\gamma}B \]  

and

\[ m_a \ll 2.5 \times 10^{-15} \text{eV} \text{ for } B_{\perp} = B_0 (1 + z)^{3/2} \]  

\[ m_a \ll 8 \times 10^{-16} \text{eV} \text{ for } B_{\perp} = B_0 (1 + z)^2 \]  

These upper bounds are more stringent than bounds obtained from the absence of high energy gamma-rays from SN 1987A (see, for example, [22]) and from the CAST experiment ([23]). Our results agree better with the propose that the observed faintness of high redshift supernovae could be attributed to the mixing of photons with a light pseudoscalar (light axion-like) particles in an intergalactic \( B \sim 10^{-9} \text{G} \) magnetic field (also see [24]).

5 Magnetic field strength and the coherent length in the Universe

The estimates of a pseudoscalar mass and the photon-pseudoscalar coupling constant depend essentially on the cosmic magnetic field in the IGM. There are some of reviews and papers concerning to the origin and possible effect of magnetic fields in the Universe and also to the current status of the art of observations of cosmic magnetic fields (see, for example, [25]-[33]).

Typical values of \( L_{coh} \) are 100 kpc - 1 Mpc which correspond to field magnitudes of 10 - 1 \( \mu \)G. For example, the case of the Coma Cluster a core magnetic field strength reaches \( B \approx 8.3 \mu_1 \text{G} \) at scales of about 1 kpc. An interesting example of clusters with a strong magnetic field is the Hydra A cluster for which the Rotation Measure (RM) implies a 6 \( \mu \)G field strength over 100 kpc superimposed with a tangled field of strength 30 \( \mu \)G ([34]). The high-resolution images of radio sources embedded in galaxy clusters show evidence of strong magnetic fields in the cluster regions, and also in the regions of cool fronts and cool fluxes ([26]). The typical central field strength is approximately 10 - 30 \( \mu \)G with the peak value as large as 10 \( \mu \)G.

As concerns to the intergalactic medium (IGM), Furlanetto and Loeb [29] estimated the magnetic field strength in the diffuse IGM assuming flux conservation for outflows from QSOs that inevitably pollute IGM. They obtained \( B_0 \leq 10^{-8} \text{G} \) and we used namely their estimate for calculating constraints on the coupling constant of photon-pseudoscalar mixing. The same value has been presented in reviews by Kronberg [25] and Grasso and Rubinstein [35].

Many authors have considered processes for generating magnetic fields of cosmological interest. Thus, Langer et al. [36] have shown that the photoionization process by photons from the first cosmic objects provides the magnetic field amplitudes as high as \( 2 \times 10^{-19} \text{G} \). Takahashi et al. [37] discussed generation of magnetic field from cosmological perturbations and showed that the amplitude of produced magnetic field could be about \( \sim 10^{-19} \text{G} \) at 10 kpc co-moving scale at present. Siegel and Fry [38] examined the generation of seed magnetic fields due to the growth of cosmological perturbations. They estimated the peak of a magnitude of these fields of \( \sim 10^{-30} \text{G} \) at the epoch of recombination.

As an example one should mention the Biermann mechanism that can produce seed fields of order \( \sim 10^{-19} \text{G} \) at redshift of \( z \approx 20 \) ([28]).

Rogachevskii et al. [39] have discussed a new mechanism of generation of intergalactic large-scale fields in colliding protogalactic clouds and emerging protostellar clouds. Self-consistent plasma-neutral gas simulations by Birk et al. [40] have shown that seed magnetic field strengths \( \lesssim 10^{-14} \text{G} \) arise in self-gravitating protogalactic clouds of spatial scales of 100 pc during \( 7 \times 10^6 \) years.

Recently Dolag et al. [41] have studied the evolution of magnetic fields in galaxy clusters with use cosmological magneto-hydrodynamic simulations. They showed that the magnetic field in core of galaxy clusters for large redshifts \( z \approx 3 \div 4 \) may reach so less magnitude as \( B \lesssim 10^{-14} \text{G} \).

Although, there exists essential dispersion of estimates of intergalactic magnetic field strength, most community prefers the magnitude of \( \sim 10^{-9} \text{G} \). Namely, the last data confirm this point of view. The analysis of the Faraday rotation of the Cosmic Microwave Background Radiation (CMBR) induced by primordial magnetic field provides the constraints on its magnitude at the level \( B \sim 10^{-9} \text{G} \) ([42]-[47]).
We use an improved limit on the axion-photon coupling from the CAST experiment to estimate the magnetic field strength into intergalactic space. Using the CERN Axion Solar Telescope (CAST), Andriamonje et al. [23] have set an upper limit on the axion-photon coupling of \( g_{a\gamma} < 8.8 \times 10^{-11} \text{GeV}^{-1} \) at 95% CL from the absence of excess X-rays from the Sun. This result is now considered as the best experimental limit over a broad range of axion masses beginning with \( m_a < 0.02 \text{eV} \). Mörtsell et al. [24] used this result for the independent estimate the probability of photon-axion oscillations in the presence of both intergalactic magnetic fields and an electron plasma. They found that the current CMB and Csaki et al. [2] data can be agreed with the intergalactic magnetic field strength \( B \sim 10^{-9} \text{G} \) in the framework of the quintessence model (\( \Omega_m = 0.3, \Omega_x = 0.7, \omega_x = -1/3 \)) if the axion mass is \( m_a \leq 10^{-10} \text{eV} \) and the coupling constant \( g_{a\gamma} \sim 10^{-14} \text{GeV}^{-1} \).

We estimate here the intergalactic magnetic field strength at \( z \sim 1 \) from the effect of extreme-scale alignments of quasar polarization vectors revealed by Hutsemekers et al. [1], using the CAST upper limit on the axion-like particle-photon mixing: \( g_{a\gamma} < 8.8 \times 10^{-11} \text{GeV}^{-1} \).

For Eq. (3) dependence \( B_\perp(z) = B_0(1 + z)^2 \) the solution of Eqs. (6) and (7) gives the next estimate: \( B_0 > 10^{-12} \text{G} \).

If we use \( B_\perp(z) = B_0(1 + z)^{3/2} \) dependence according to the Chandrasekhar-Fermi law one obtains \( B_0 > 4 \times 10^{-10} \text{G} \).

Our estimates of the intergalactic magnetic field strength presented here lie in limits of modern theoretical predictions.

6 Conclusions

We estimate the photon-pseudoscalar boson mixing constant from the effect of cosmological alignment and cosmological rotation of polarization of distant QSOs revealed by Hutsemekers et al. [1]. This effect can be explained in terms of birefringent phenomenon due to photon-pseudoscalar particle mixing in a cosmological magnetic field.

We explore two model dependences of cosmological magnetic field on redshift: quadratic form of \( B(z) = B_0(1 + z)^2 \) and \( B(z) = B_0(1 + z)^{3/2} \). The last relation is based on the Chandrasekhar-Fermi law.

We obtained the best low constraints on the pseudoscalar-photon coupling constant: \( g_{a\gamma} \leq 4 \times 10^{-14} \text{GeV}^{-1} \).

On the contrary, one can estimate the strength of the cosmic magnetic field using the constraints on the axion-like particle-photon coupling constant from the CAST experiment and from SNe Ia dimming effect ([2]). In a result, we obtain the magnitude of the intergalactic magnetic field \( (z \sim 1 \div 2) \) at the level of about \( 4 \times 10^{-11} \div 10^{-10} \text{G} \).

Acknowledgements

We would like to thank for the support by the RFBR (project No. 07-02-00535a), Program of Prezidium of RAS "Origin and Evolution of Stars and Galaxies", the program of the Department of Physical Sciences of RAS "Extended Objects in the Universe".

This research was supported also by the Grant of President of Russian Federation "The Basic Scientific Schools" NS.6110.2008.2.

M.Yu. Piotrovich acknowledges the Council of Grants of President of Russian Federation for Young Scientists Grant No. 4101.2008.2.

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