Axions and CMB Spectral distortions in Cosmic Magnetic Field

Damian Ejlli

Theory group, INFN Laboratori Nazionali del Gran Sasso, 67100 Assergi, L'Aquila Italy
Department of Physics, Novosibirsk State University, Novosibirsk 630090, Russia

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In this paper I discuss the impact of photon axion-mixing in the early Universe. Interaction of CMB photons with large scale cosmological magnetic fields can produce axions or other pseudoscalar particles. This process in the early Universe would distort the CMB spectrum and also create a measurable temperature anisotropy. New limits on axion mass and magnetic field strength are presented.

1 Introduction

One of the most striking predictions of the standard cosmology is the existence of the Cosmic Microwave Background (CMB) radiation. The CMB has been experimentally observed and its temperature has been measured with a great precision, $T = 2.725 \pm 0.001$ K by several experiments. An extremely important feature of the CMB is that it presents very small spatial temperature anisotropy of the order $\delta T/T \simeq 10^{-5}$. Apart from this observational fact, the CMB is expected to have additional features that are intrinsically connected with its spectrum.

Indeed, another prediction of the standard cosmology is that the CMB spectrum may present very small spectral distortions that may have been generated before or after the recombination epoch. In general these distortions are labelled as μ, i, y type distortions and are formed in different cosmological epochs. Until today there has not been observed any CMB spectral distortions but only upper limits on the distortion parameters exist. The COBE/FIRAS experiment [1] put only upper limits on μ and y with values $|\mu| < 9\times10^{-5}$ and $|y| < 1.5\times10^{-5}$.

Despite the fact that there has not been observed any CMB spectral distortions, the standard cosmological model predicts them and are generated by processes which heat, cool, scatter and create photons. Most of these processes are in general connected with new physics but there are also several ones that are connected with very well known physics. Mechanisms that might produce spectral distortions by injecting energy and photons in the plasma include: evaporating primordial black holes, decaying of relic particles, dark matter annihilation, tangled cosmological magnetic fields, etc. On the other hand, there are also processes that tend to erase any spectral distortion that might be created in the CMB and attempt to restore the full thermal equilibrium.

Obviously there is a competition between processes that tend to distort the CMB spectrum and those that tend to restore it. As shown in Ref. [2] the CMB spectrum would be distorted only if energy injection occurs after a certain cosmological time or cosmological redshift. In the standard model of CMB spectral distortions, the spectrum will acquire a μ distortion if energy is injected in the redshift interval $2 \times 10^5 \lesssim z \lesssim 2 \times 10^6$. In this case the CMB spectrum is a Bose-Einstein distribution. For later times or cosmological redshifts, if there is any energy injection at $z \lesssim 1.5 \times 10^5$ the spectrum will acquire a y type distortion. Here the i type distortion is not discussed [3].

Among the sources that may generate spectral distortion, axion production in magnetic field is one of the best candidates. Indeed, in the presence of large scale magnetic fields axions may be efficiently produced before and after the decoupling time. At this point it would be natural to ask which is the impact of CMB photon-axion mixing on spectral distortions. If there is an impact, which is the mass range of axions that create spectral distortions, etc. Before answering to these questions it is important to first discuss the nature and strength of the cosmological magnetic field. This is done in Sec. 2, and in Sec. 3 we discuss the impact of photon-axion mixing on spectral distortions and temperature anisotropy.

2 Cosmological magnetic fields

One of the most fascinating problems in modern cosmology is whether primordial magnetic fields exist or not. Based on several astrophysical observations they seem to be everywhere in the Universe. They are present in our solar system, in stars, in the Milky way, in low and high redshift galaxies, in galaxy clusters, in superclusters and in voids of large scale structure (LSS). Their strength in galaxies is of the order of few to ten μG independently on the redshift while in clusters is of the order of μG. Their generation mechanism still remains an open question; however, the general consensus at present time is that they are thought to be produced by amplification of pre-existing weaker magnetic fields via different types of dynamo and via flux-conserving compression during the gravitational collapse of an accompanying structure formation.

The dynamo and amplification mechanisms can act only if an initially non-zero magnetic field is present. This seed field for the amplification might be very small, but it has to be generated by a different mechanism, which pre-dates the structure formation epoch or operates at the onset of structure formation. Two main models are widely accepted: either it is produced in the early Universe prior to the epoch of LSS or it is produced during gravitational collapse at the start of LSS. The existing data on magnetic fields in galaxies and galaxy clusters cannot provide direct constraints on the properties and origin of the seed fields. Therefore the only potential opportunity for understanding the nature of the initial seed fields is to search for places in the Universe where these fields might exist in their original form, namely in the intergalactic medium (IGM) and in the voids of LSS.

The spatial structure of large scale magnetic fields can be divided in two categories: large scale uniform magnetic fields (spatially homogeneous) and inhomogeneous magnetic fields (tangled magnetic fields). The former category was considered for the first time by Zel'dovich and Thorne [4]. Indeed, if there existed a large scale homogeneous magnetic field in the early Universe, it would induce a preferred direction during Universe expansion and therefore would break the Universe isotropy (every direction is the same). In this case the metric is not given anymore by a FRW one but by a Bianchi type IX metric.

The metric for a homogeneous magnetic directed along the z axis is given by:

$$ds^2 = dt^2 - a^2(t)(dx^2 + dy^2) - b^2(t)dz^2, \tag{1}$$

where $a(t)$ is the cosmological scale factor in the x, y direction and $b(t)$ is the scale factor along the z direction. In an anisotropic Universe, the energy momentum tensor of the electromagnetic field is also anisotropic. This implies that along the x, y axis there is a positive pressure induced that would tend to decelerate the Universe and there is a negative pressure induced along the z axis that tends to accelerate the Universe. Following Zel'dovich, one can formally calculate which is the induced temperature anisotropy by an anisotropic expansion of the Universe as follows:

$$\frac{T_x - T_z}{T_{rec}} \simeq -\frac{1}{2}\int_{t_{rec}}^{t_0} \sigma d(\ln t), \tag{2}$$

where $\alpha = \dot{a}/a, \beta = \dot{b}/b$ and $\sigma = \alpha - \beta$ and T_{rec} is the CMB temperature at the recombination time. If we use the present constraint on the CMB temperature anisotropy, it is possible to reverse Eq. 2 and use it as a constraint on the magnetic field strength at present epoch. For $\Delta T/T \simeq 10^{-5}$ [1] one finds an upper limit on the strength of magnetic field $B \lesssim 3$ nG [4].

In the case of inhomogeneous magnetic fields, there are several models that predict magnetic fields with no homogeneous term or tangled magnetic fields [5]. In this case one assumes that the magnetic field is statistically homogeneous and isotropic with a two point correlation function

$$\langle B_i(\mathbf{k}) B_j^*(\mathbf{q})\rangle = \delta^3(\mathbf{k} - \mathbf{q}) P_{ij}(\mathbf{k}) P_B(k), \tag{3}$$

where P_{ij} is a projection tensor and P_B is the power spectrum of the primordial magnetic field that in general is assumed to be a power law, $P_B = Ck^{n_B}$ with C a constant and n_B the spectral index of the magnetic field. For this type of magnetic field configuration, limits on the magnetic field strength are model dependent. For example from the CMB angular temperature anisotropy, the limit on magnetic field strength at scale $\lambda_B \simeq 1$ Mpc is $B_\lambda \lesssim 3 \times 10^{-9}$ [6]. On the other hand, Faraday rotation of the CMB polarization can be used to constrain the magnetic field strength on a given mode scale λ_B and a spectral index n_B as shown in Fig. 1.

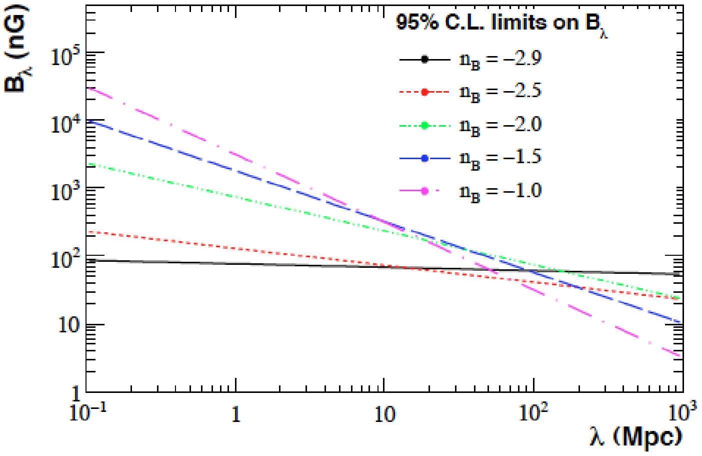

Figure 1: Limits on the magnetic field strength B_λ vs. λ_B from Faraday polarization of CMB as shown in Ref. [7]

3 Axion production in cosmological magnetic fields

In Sec. 2 we discussed about the spatial structure and strength of large scale magnetic fields for two different spatial configurations. It is well known that in the presence of a magnetic field photons can mix with axions and eventually oscillate into them in macroscopic B-fields. Therefore a natural question that comes is which is the impact of such mechanism on CMB spectral distortions. This process was studied in Refs. [8, 9] in the case of large scale uniform magnetic fields and tangled magnetic fields. In general to study such a process for the CMB case, it is necessary to take into account coherence breaking in the cosmological plasma. This is done by working with the density matrix ρ of the photo-axion system that obeys the following kinetic equation:

$$\frac{d\rho}{dt} = i[M, \rho] - \{\Gamma, (\rho - \rho_{eq})\}, \tag{4}$$

where M is the mixing matrix between the photon states and the axion and is given by the Raffelt-Stodolsky matrix equation as shown in Ref. [10].

In the case of large scale uniform magnetic fields, new limits on the axion mass and magnetic field strength are found. If we require that the resonant photon-axion mixing occurs during the μ epoch, one finds constraints on the axion mass (see Ref. [8]) in the range

$$2.66 \times 10^{-6}\,\mathrm{eV} \lesssim \bar{m}_a \lesssim 4.88 \times 10^{-5}\,\mathrm{eV}, \tag{5}$$

where $\bar{m}_a$ is the resonant axion mass during the μ epoch. By requiring that CMB μ distortion is totally due to photon-axion mixing one finds a simple relation between the magnetic field strength B_{nG} (in units of nano gauss), the CMB μ parameter and the resonant axion mass $\bar{m}_a$ as follows

$$B_{\mathrm{nG}} = 6.76 \times 10^{-2}\, \frac{\sqrt{\mu}}{\bar{m}_a\, C_{a\gamma}}, \tag{6}$$

where $C_{a\gamma}$ is a constant that essentially depends on the QCD axion model (KSVZ or DFSZ). In Fig. 2 the exclusion plot for COBE and the sensitivity plot for PIXIE/PRISM [11] in the case of KSVZ and DFSZ axions models in the $B - \bar{m}_a$ plane, are shown.

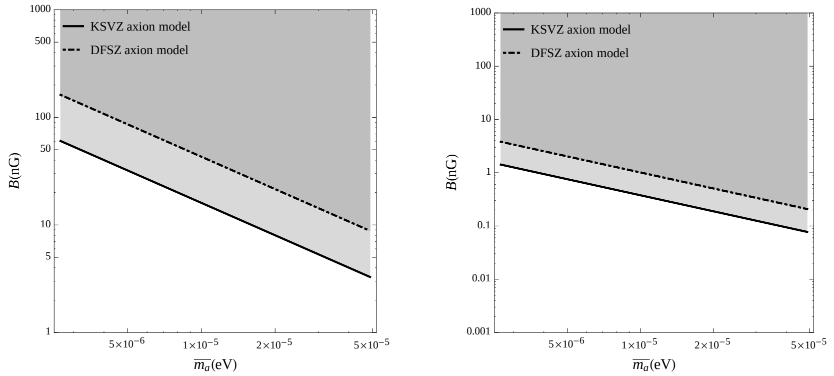

Figure 2: Exclusion plot on the left for the COBE limit on μ distortion and the sensitivity plot on the right for the PIXIE/PRISM sensitivity limit on μ for different axion models as shown as in Ref. [8].

In the case of axion production in tangled magnetic fields the situation slightly changes because in this case the magnetic field itself would produce a CMB μ distortion. As shown in Ref. [9] one needs to modify Eq. (6) in order to include dissipative effects of tangled magnetic fields. In this case Eq. (6) is modified as follows:

$$B_{\rm nG} = \sqrt{\mu}\left(1.6\times 10^{3}\, C_{n_B}^{-1/2}(\lambda_B/\lambda_D)^{-(\frac{n_B+3}{2})} + 3.38\times 10^{-2}\frac{1}{\bar{m}_a\, C_{a\gamma}}\right), \quad (\lambda_B \ll \lambda_D) \tag{7}$$

for $\lambda_B \ll \lambda_D$. Here λ_D is the damping scale of the tangled magnetic field, λ_B is its wave-mode and C_{n_B} is a numerical factor. On the other hand for $\lambda_D \ll \lambda_B$ one finds

$$B_{\rm nG} = \sqrt{\mu}\left(1.6\times 10^{3}\, D_{n_B}^{-1/2}(\lambda_B/\lambda_D) + 3.38\times 10^{-2}\frac{1}{\bar{m}_a\, C_{a\gamma}}\right), \quad (\lambda_D \ll \lambda_B), \tag{8}$$

where D_{n_B} is a numerical constant. In Fig. 3 the exclusion plot of COBE and the sensitivity plot of PIXIE/PRISM [11] in the case of KSVZ axion model and spectral index $n_B = 3$ for different axion masses are shown.

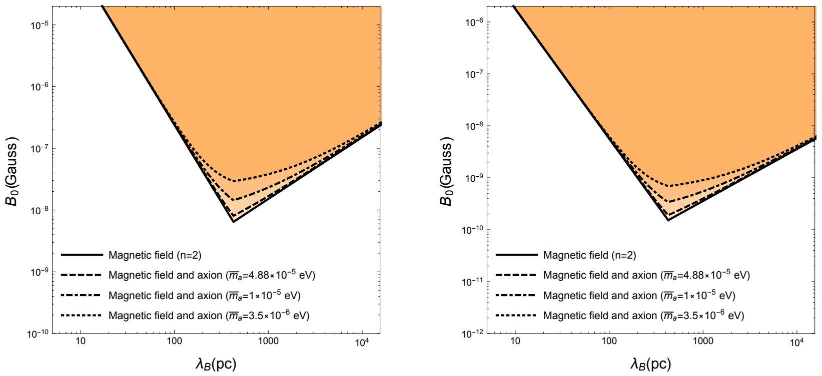

Figure 3: On the left the exclusion plot for the COBE limit on μ, KSVZ axion model and magnetic field spectral index $n_B = 2$. On the right the sensitivity plot of PIXIE/PRISM for the expected limit on μ, KSVZ axion model and $n_B = 2$ is shown.

4 Conclusions

Again the CMB turns out to be one of the most important ways that we have to test fundamental physics in different ways. It can couple to the large scale magnetic fields present in the early Universe and mix with low mass bosons such as axions, axion like particles, scalar bosons and gravitons. In the case of axions its production probability essentially depends on the coupling constant of axions to two photons $g_{a\gamma}$ or its mass, photon/axion energy ω and magnetic field strength.

Axions are extremely important for the standard model of particle physics since they allow to solve the strong CP problem. However, there is an inconvenient with them because we neither know their mass nor their coupling constant to photons. The only way that we have at present to study them is by direct experimental searches or looking for their impact indirectly. In the latter case the CMB turns out to be extremely important in this regard.

Here we have shown that the coupling of CMB photons with the cosmological magnetic field can generate CMB μ distortions prior to the recombination epoch. This allows us to speculate on the axion mass and magnetic field strength at present time. In the case of a homogeneous magnetic field, it is found that for the magnetic field upper limit of $B \lesssim 3.2$ nG one would constrain the axion mass to be $m_a \lesssim 4.8 \times 10^{-5}$ eV for the KSVZ axion model, see Fig. 2 left panel. On the other hand, using the value of excluded axion mass $m_a \simeq 3.5 \times 10^{-6}$ eV from the ADMX experiment [12] together with the COBE bound on μ, we find the limit $B \simeq 46$ nG for the KSVZ axion model and $B \simeq 130$ nG for the DFSZ axion model, for a homogeneous magnetic field with coherence length at the present epoch $\lambda_B \simeq 1.3$ Mpc [8].

In the case of tangled magnetic field we find new limits on the magnetic field strength that are in general weaker in comparison with other studies. These limits are obviously model dependent and essentially depend on the magnetic field cut-off scale λ_B [9] and the spectral index n_B. For example by using the COBE upper limit on μ and for the magnetic field scale $\lambda_B \simeq 415$ pc, a weaker limit in comparison with other studies on the magnetic field strength ($B_0 \leq 8.5 \times 10^{-8}$ G) up to a factor 10 for the DFSZ axion model and the axion mass $m_a \geq 2.6 \times 10^{-6}$ eV is found. A forecast for the expected sensitivity of PIXIE/PRISM on μ is also presented. If CMB μ distortion could be detected by the future space missions PIXIE/PRISM and assuming that the strength of the large scale uniform magnetic field is close to its canonical value, $B \simeq 1 - 3$ nG, axions in the mass range $2\,\mu$eV - $3\,\mu$eV would be potential candidates of CMB μ distortion.

Acknowledgments

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