Photon-axion oscillations – further results

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In a previous work [1] we have studied the possibility that high energy (∼TeV) photons emitted by distant sources can evade absorption by background photons (through the reaction $\gamma\gamma_{BGK} \to e^+e^-$) by means of conversion into axion-like particles through the mechanism of photon axion oscillations. This mechanism was invoked in the past [2] to explain the anomalous transparency of the Universe to high energy photons, recently confirmed in [3].

Axion-like particles (ALP's) with a two-photon vertex are predicted in many extensions of the Standard Model. Pseudoscalar ALP's couple with photons through the following effective Lagrangian [4]

$$\mathcal{L}_{a\gamma} = -\frac{1}{8} g_{a\gamma} \epsilon_{ijkl} F^{ij} F^{kl} a \,, \tag{1}$$

where a is the ALP field with mass m_a, F^{ij} the electromagnetic field-strength tensor, and $g_{a\gamma}$ the ALP-photon coupling. As a consequence of this coupling, ALP's and photons do oscillate into each other in an external magnetic field. The evolution equation for photon moving in the x_3 direction can be written as [1]

$$\frac{\partial}{\partial x_3} \left(\begin{array}{c} A_1 \\ A_2 \\ a \end{array} \right) = -i\mathcal{H} \left(\begin{array}{c} A_1 \\ A_2 \\ a \end{array} \right) . \tag{2}$$

In the high energy limit ($E \geq 100$ GeV) the hamiltonian $\mathcal{H}$ can be written as

$$\mathcal{H} = \left[\begin{array}{ccc} -i\frac{\Gamma_\gamma(E)}{2} & 0 & \frac{g_{a\gamma}B_T}{2} c_\phi \\ 0 & -i\frac{\Gamma_\gamma(E)}{2} & \frac{g_{a\gamma}B_T}{2} s_\phi \\ \frac{g_{a\gamma}B_T}{2} c_\phi & \frac{g_{a\gamma}B_T}{2} s_\phi & 0 \end{array} \right] . \tag{3}$$

Here $\mathbf{B}_T = \mathbf{B} - B_3\mathbf{e}_3$ is the transverse component of the external magnetic field, $c_\phi \equiv \cos\phi = \mathbf{B}_T \cdot \mathbf{e}_1/B_T$, and Γ_γ is the absorption rate for the pair production process.

In [1] we have modeled the extragalactic magnetic field as cells where the magnetic field is randomly oriented and constant strength of the order of ~ 1 nG. The coherence length of each cell is $L \sim 1$ Mpc. Within this model we have found also an analytical result for the evolution of the average on all possible realizations of the magnetic field in the cells for the "transfer function", i.e. the probability that an unpolarized photon emitted in the initial state is detected as a photon in the final state. However, we want to go beyond this simple cell model. In particular there are two models that are much more realistic: 1) The turbulent model; 2) The "frozen model".

In the first model the intergalactic $\mathbf{B}$ field is an isotropic and homogeneous gaussian turbulent magnetic field with 0 mean and r.m.s. value $\mathcal{B}^2$. For such a field each component can be expanded in Fourier modes:

$$B_i(\mathbf{x}) = \int \frac{d^3k}{(2\pi)^3} \tilde{B}_i(\mathbf{k}) e^{i(\mathbf{k}\cdot\mathbf{x}+\phi(\mathbf{k}))} \,. \tag{4}$$

The correlation function for the Fourier modes for the components of an isotropic and homogeneous magnetic field can be written as:

$$\langle \tilde{B}_i(\mathbf{k}) \tilde{B}_j(\mathbf{k}') \rangle = (2\pi)^6 M(k) P_{ij}(\mathbf{k}) \delta^3(\mathbf{k}-\mathbf{k}') \,, \tag{5}$$

were $k = |\mathbf{k}|$, the tensor

$$P_{ij}(\mathbf{k}) = \left(\delta_{ij} - \frac{k_i k_j}{k^2} \right) \tag{6}$$

assures the condition $\nabla \cdot \mathbf{B} = 0$, $M(k)$ is the spectrum of perturbation normalized in such a way that the r.m.s. coincides with $\mathcal{B}^2$:

$$\mathcal{B}^2 = \langle B_i(\mathbf{x}) B^i(\mathbf{x}) \rangle = 8\pi \int_0^\infty dk\, k^2 M(k) \,. \tag{7}$$

We consider a typical power-law spectrum with an ultraviolet cut-off: $M(k) = Ak^q \Theta(k - k_c)$. A typical example is the *Kolmogorov spectrum* with $q = -5/3$.The UV cutoff $k_c \sim l_c^{-1}$ is the inverse of coherent scale, which is chosen of the order of ~ 1 Mpc. After generating a big number of random turbulent realizations we have found that the results are not much different from those obtained with the cell method. This can be understood from the fact that the coherence function $C(\xi) = \langle B_i(x_3) B_i(x_3 + \xi) \rangle$, with $i = 1, 2$, has a width of the order of the coherence length (~ 1 Mpc) which is much more smaller than the typical photon-axion oscillation length (~ 100 Mpc). This model is thus almost equivalent to a δ-correlated model (i.e. $C(\xi) \propto \delta(\xi)$) which is in turn equivalent to a gaussian cell model with $L_{coherence} \ll \lambda_{osc}$.

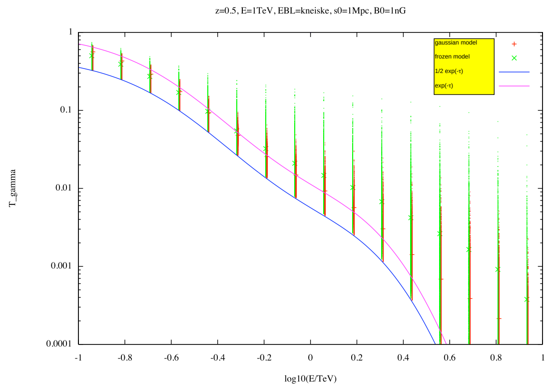

Figure 1. Photon transfer function T_γ as function of the photon energy E for different realizations of the magnetic field both for gaussian (red) and for log-normal (frozen) models. The crosses indicate the average of the distributions. The continuous lines are the lower limit of the distributions (purple line) and the T_γ in absence of photon-axion conversion.

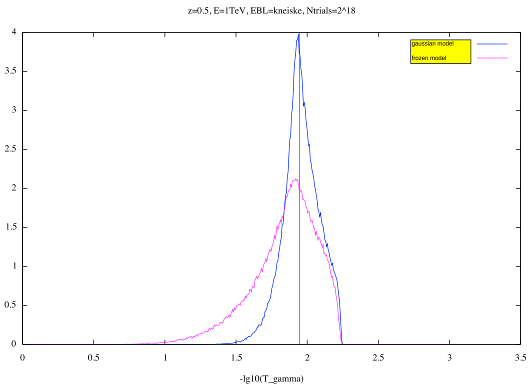

Figure 2. Probability density function for the $-\log_{10} T_\gamma$ at fixed energy ($E = 1$ TeV) for gaussian (red) and log-normal (frozen) models. The red line indicates the T_γ in absence of photon-axion conversion.

A more promising model is the so called "B-frozen-in-the-plasma" model. This is equivalent to the cell model but it is assumed that the strength of the magnetic field is proportional to $n_e^{2/3}$ (due to flux conservation), where n_e is the electron density, which in turn follows the matter density. To simulate the overdensities due to cluster clumps, the distribution of n_e is assumed log-normal with a given (z-dependent) average and r.m.s. In this model, the field is almost zero in almost all the space but can assume large values in specific cells. In particular realizations one can have massive conversion of photons into axions close to the source and reconversion close to the Earth. For those realizations the mechanism of conversion is much more efficient and the transparency is much higher than in the gaussian cell model and the turbulent model.

This fact can be seen in Fig. 1 where the T_γ as function of energy for a source at $z = 0.5$ as been plotted for many realizations of the cell magnetic field both for the gaussian and for the frozen model. We see that in the last case for some realizations the T_γ extend to higher values respect to the case of the gaussian model. This is very promising since the frozen model is believed to be a more realistic description of the magnetic field of the Universe [5].

In Fig. 2 we also show the Probability Density Function for the (decimal logarithm of) T_γ at fixed energy ($E = 1$ TeV) and source distance ($z = 0.5$). From Figs. 1 and 2 we realize that within the frozen model there is a non zero probability that high energy photons can reach the Earth also from cosmological distance with a modest absorption. This could explain the recent observation of high energy sources at high distances [3].

The previous results will be published soon. We plan also to extend our results by studying the effects of the local magnetic field of the host galaxy/cluster and the effect of reconversion in the magnetic field of our galaxy.

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