ALPs in the Sky:
New Bounds and Discovery Opportunities

Alessandro Mirizzi

II Institut für Theoretische Physik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

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Very light axion-like particles (ALPs) with a two-photon vertex are predicted in many extensions of the Standard Model. The two-photon coupling would induce the mixing with ALPs for photons emitted by distant astrophysical sources, and propagating in the large-scale cosmic magnetic fields. In this context, we discuss how current and upcoming astrophysical experiments, ranging from the cosmic microwave background to the high-energy gamma-rays, could probe the elusive ALPs in a region of their parameter space not accessible by laboratory experiments.

1 Introduction

Axion-like particles (ALPs) with a two-photon vertex are predicted in many extensions of the Standard Model (see [1] for a recent review). The $a\gamma\gamma$ coupling allows for ALP-photon conversions in electric or magnetic field. This effect is exploited by the ADMX experiment to search for axion dark matter, by CAST to search for solar axions, and by regeneration laser experiments. Due to their two-photon vertex, ALPs can also play an intriguing role in astrophysics. Indeed, photons emitted by distant sources and propagating through large-scale cosmic magnetic fields can mix with ALPs. As a consequence, two peculiar effects can arise. One is photon-ALP conversion (oscillation) and the other consists in the change of the polarization state of photons. Both these effects can be exploited to look for signatures of ALPs in astrophysical observations.

The outline of this talk is as follows. In Section 2 we review the mechanism of photon-ALP mixing in a magnetic field. In Section 3 we show how photon-ALP conversions in primordial magnetic fields in the Early Universe would have distorted the blackbody spectrum of the cosmic microwave background (CMB). Therefore, using the current high precision CMB spectral data one can obtain a strong bound on photon-ALP mixing. In Section 4 we discuss the impact of photon-ALP conversions on the polarization of distant gamma-ray bursts. Finally, in Section 5 we discuss about the impact of ALP conversions on the spectra of very high-energy gamma sources, in particular in relation with the surprising degree of transparency of the universe, recently measured by gamma-ray telescopes.

2 Photon-ALP conversions

ALPs and photons oscillate into each other in an external magnetic field due to the interaction term [2]

$$\mathcal{L}_{a\gamma} = -\frac{1}{4}\, g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma} \mathbf{E} \cdot \mathbf{B}\, a\,, \tag{1}$$

where $F_{\mu\nu}$ is the electromagnetic field tensor, $\tilde{F}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma}$ is its dual, a is the ALP field, and $g_{a\gamma}$ is the ALP-photon coupling. For a homogeneous magnetic field one may choose a coordinate system aligned with the field direction. The linear photon polarization state parallel to the transverse field direction $\mathbf{B}_T$ is denoted as $A_\parallel$ and the orthogonal one as $A_\perp$. Then, the probability for a photon emitted in the state $A_\parallel$ with energy ω to convert into an ALP after traveling a distance s is [2]

$$P_0(\gamma \to a) = \left|\langle A_\parallel(0)|a(s)\rangle\right|^2 = \sin^2(2\vartheta)\sin^2(\Delta_{\rm osc} s/2) = (\Delta_{a\gamma} s)^2 \frac{\sin^2(\Delta_{\rm osc} s/2)}{(\Delta_{\rm osc} s/2)^2}\quad , \tag{2}$$

where the oscillation wavenumber is given by

$$\Delta^2_{\rm osc} = (\Delta_{\rm pl} - \Delta_a)^2 + 4\Delta^2_{a\gamma}\,. \tag{3}$$

Here $\Delta_a = -m_a^2/2\omega$, $\Delta_{\rm pl} = -\omega_{\rm pl}^2/2\omega$, $\Delta_{a\gamma} = g_{a\gamma}|\mathbf{B}_T|/2$, and $\omega_{\rm pl}^2 = 4\pi\alpha\, n_e/m_e$ defines the plasma frequency, m_e being the electron mass and α the fine-structure constant.

It proves useful to define a *low critical energy*

$$E_L \equiv \frac{E\,|\Delta_a - \Delta_{\rm pl}|}{2\,\Delta_{a\gamma}} \simeq \frac{25\,|m^2 - \omega^2_{\rm pl}|}{(10^{-13}{\rm eV})^2}\left(\frac{10^{-9}{\rm G}}{B_T}\right)\left(\frac{10^{-11}{\rm GeV}^{-1}}{g_{a\gamma}}\right){\rm keV} \tag{4}$$

In the energy range $E \gg E_L$ the photon-ALP mixing is maximal ($\vartheta \simeq \pi/4$) and the conversion probability becomes energy-independent. This is the so-called *strong-mixing regime*. Outside this regime the conversion probability turns out to be energy-dependent and vanishingly small.

Cosmic magnetic fields components have a quite complicated and poorly known morphology, so that it has become customary to suppose that they possess a domain-like structure with varying coherence lengths. The propagation over many random B-field domains is a truly 3-dimensional problem, because different photon polarization states play the role of $A_\parallel$ and $A_\perp$ in different domains. This is enough to guarantee that the conversion probability over many domains is an incoherent average over magnetic field configurations and photon polarization states. The probability after travelling over a distance $r \gg s$, where s is the domain size, is *on average* [3]

$$P_{\gamma\to a}(r) = \frac{1}{3}\left[1 - \exp\left(-\frac{3P_0\, r}{2s}\right)\right]\,, \tag{5}$$

with P_0 given by Eq. (2). As expected one finds that for $r/s \to \infty$ the conversion probability saturates, so that *on average* one third of all photons converts into ALPs. However, due to the stochastic behavior of the photon-ALP conversions in the random magnetic fields, on different lines of sight one can find $\mathcal{O}(1)$ variations with respect to the average value.

Finally, we mention that besides the conversion between photons and ALPs, there is a more subtle effect induced by the ALP two-photons vertex. Indeed, as a consequence of the loss of $\parallel$ photons into ALPs, the amplitude of the $\parallel$ mode with respect to the $\perp$ is depleted. This would lead to a rotation of the plane of polarization that can also lead to interesting signatures in astrophysical observations.

3 Resonant Conversions in the Early Universe

The presence of primordial magnetic fields would inevitably produce resonant conversions between photons and ALPs in the Early Universe, when the condition $m_{\rm a} = \omega_{\rm pl}$ is satisfied [4]. Depending on the ALP mass, these conversions could have taken place in different epochs during the thermal history of the Universe. For ALP masses ($m_a < 10^{-9}$ eV) undergoing resonant conversions after the recombination epoch, one can obtain constraints on this mechanism from the the spectral distortions induced on the CMB spectrum. Using the high precision CMB spectral data collected by the FIRAS instrument on board of the Cosmic Background Explorer, one gets as limit on the product of the ALP-photon coupling $g_{a\gamma}$ times the sky and polarization averaged magnetic field B [4]

$$gB < 10^{-13} - 10^{-11}\ \ {\rm GeV}^{-1}\ \ {\rm nG}\ \ . \tag{6}$$

For photon-ALP conversions occurring during the "weak-coupling" regime (10^{-9} eV $< m_a <$ 10^{-4} eV) the bound $gB < 10^{-11}{\rm GeV}^{-1}{\rm nG}$ occurs. Slightly weaker bounds were also derived for higher ALP masses.

Therefore, if a primordial magnetic field would eventually be found with values close to the current upper bound $B \simeq 1$ nG, the resulting CMB limit on the coupling $g_{a\gamma}$ for very light ALPs would overcome the barrier placed by current experimental and astrophysical bounds. Conversely, if ALPs will be eventually discovered improving the current sensitivity of the solar axion helioscope CAST, or with new techniques in laser experiments, this cosmological argument will provide a complementary constraint on the strength of the primordial magnetic field.

4 Polarization of cosmic gamma-ray bursts

Measuring the polarization of prompt gamma-ray burst (GRB) emission in the keV-MeV range represents one of the main challenges for high-energy astronomy of the next decade. Various polarimetric missions are currently being developed, which are expected to collect an all-sky rich sample of GRBs so as to allow for a meaningful statistical analysis of their polarization properties. As recently realized, important conclusions concerning the GRB emission models are expected to be drawn from these studies.

In [5] it has been shown that the existence of ALPs with parameters lying in experimentally allowed ranges drastically modifies the GRB polarization pattern. More specifically, cosmic magnetic fields of extragalactic, intracluster and Galactic origin along the line of sight to a GRB act as catalysts for significant photon-ALP mixing. In particular, due to the random structure of the extragalactic and intracluster magnetic fields, the amount of photon-ALP mixing strongly depends on the orientation of the line of sight. Therefore, starting with a given source polarization a broad statistical distribution is expected to be detected when observing GRBs from different directions in the sky. The observation of these peculiar broad distributions would hint at the existence of very light ALPs. In general, the presence of very light ALPs ($m_a < 10^{-13}$ eV) can play a role for values of the photon-ALP coupling constant $g_{a\gamma} < 10^{-11}$ GeV^{-1}, namely one order of magnitude lower than the current experimental limit set by the CAST experiment.

5 Transparency of the Universe to Very High-Energy photons

In the last recent years photon-ALP conversions have been proposed as a mechanism to avoid the opacity of the extragalactic sky to high-energy radiation due to pair production on the Extragalactic Background Light (EBL). At this regard, recent observations of cosmologically distant gamma-ray sources by ground-based gamma-ray telescopes have revealed a surprising degree of transparency of the universe to very high-energy (VHE) photons ($E \gtrsim 100$ GeV). Surprisingly, data seem to require a lower density of the EBL than expected and/or considerably harder injection spectra than initially thought. At this regard, oscillations between very high-energy photons and ALPs (with $m_a < 10^{-10}$ eV and $g_{a\gamma} \simeq 10^{-11}$ GeV^{-1}) in the random extragalactic magnetic fields [6] would represent an intriguing possibility to explain this puzzle through a sort of "cosmic light-shining through wall" effect.

It has been then realized [7] that the turbulent structure of the extragalactic magnetic fields would produce a stochastic behavior for the photon-ALP conversions along different lines of sight, producing both an enhancement or a suppression in the observable photon flux with respect to the expectations with only absorption. As a consequence, the most striking signature of the mixing with ALPs would be a reconstructed EBL density from TeV photon observations which appears to vary over different directions of the sky: consistent with standard expectations in some regions, but inconsistent in others. This effect is testable with the measurements of the new generation of Imaging Atmospheric Cherenkov Telescopes, and hopefully with the future Cherenkov Telescope Array.

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