Axion-like particles and the propagation of gamma rays over astronomical distances

S. V. Troitsky

Institute for Nuclear Research of the Russian Academy of Sciences,
60th October Anniversary prospect 7A, 117312 Moscow, Russia

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In this mini-review, possible manifestations of mixing between axion-like particles (ALPs) and energetic photons propagating over astronomical distances are considered. We discuss the evidence for the anomalous transparency of the Universe from observations of ensembles of distant gamma-ray sources, present the general formalism for the ALP-photon mixing and explain how this mechanism may remove the anomaly. We present relevant values of ALP parameters and discuss future ways to verify the scenario and to discover the particle in question.

1. INTRODUCTION

The axion [1, 2, 3] is a hypothetical pseudoscalar particle coupled to gluons, originally invoked to solve the strong CP problem. Its characteristic feature is a two-photon coupling which is used to search for axions both in laboratory experiments and in astrophysical observations. In various axion models, the mass of the pseudoscalar $m$ is related to the two-photon coupling $g_{a\gamma\gamma}$ as

$$g_{a\gamma\gamma} = 10^{-10} \text{ GeV} = C \frac{m}{1 \text{ eV}},$$

where $C$ is a constant of order one. It is a nontrivial task to solve the strong CP problem if the condition $|g_{a\gamma\gamma}|$ is not satisfied (see however Refs. [4, 5, 6]), but light pseudoscalars which do not obey the relation (1) arise in numerous extensions of the Standard Model of particle physics (see e.g. Ref. [7] for a review). These particles are called axion-like particles (ALPs). Depending on their interactions, they may constitute the dark matter, or a part of it [8]. As we will see below, the existence of a particle of this kind with certain parameters is actually favoured by recent astronomical observations.

2. ANOMALOUS TRANSPARENCY OF THE UNIVERSE

Thanks to the ALP-photon interaction, conversion of a photon to ALP and back may happen in the external magnetic field (see Sec. 3. for a quantitative description). Since ALP interactions are very weak, this particle penetrates the media which is non-transparent for photons. This mechanism allows for the classical “light shining through the wall” experiment, in which photons are supposed to convert to axions or ALPs and back on either side of a nontransparent wall. Here we note that this experiment is continuously being repeated at the scale of the Universe. Indeed, the Universe is filled with diffuse radiation of various frequencies. Energetic photons scatter on the soft background radiation when propagating through the Universe by producing electron-positron pairs [9]. For gamma rays with energies between 100 GeV and a few TeV, the principal target is the infrared background. The density of background infrared photons is poorly known experimentally but can be constrained from below by summing the observed light from galaxies [10]. The mean free path of $\sim$TeV gamma rays with respect to the pair production does not exceed dozens of Megaparsecs. However, a lot of more distant TeV sources have been detected [11]. While, in each particular case, this might be explained by unusual hardening of the emitted spectrum at high energies, no working mechanism resulting in this hardening is known [12]. Moreover, this interpretation is not supported by the analysis of the ensemble of all observed sources. Even for the most conservative models of the infrared background, strength and positions of upward breaks in the emitted spectra of distant blazars are redshift-dependent, indicating incorrect account of the absorption (anomalous transparency of the Universe).
Indeed, atmospheric Cerenkov telescopes, as well as Fermi LAT, continue to discover very-high-energy (VHE, energies larger than 100 GeV) gamma radiation from distant sources \cite{12, 13, 14}. Additional suppression of the VHE flux from distant sources with respect to that of similar astrophysical objects located close to the observer is expected and, indeed, has been observed in the Fermi-LAT data \cite{15}. It is, unfortunately, hardly possible to compare the observed suppression with the one expected theoretically. The reason is that the relevant EBL density is poorly known (see e.g. Refs. \cite{16, 17} for reviews). To measure the extragalactic infrared background while staying within the Solar system is a challenge because of the overwhelming contribution of the Zodiacal light. Existing theoretical models of the EBL give different predictions. However, the lowest possible amount of intergalactic infrared light is constrained \cite{10} by simple counting of contributions from observed galaxies.

The distant gamma-ray sources under discussion are blazars, that is active galactic nuclei with relativistic jets pointing to the observer. The mechanism of high-energy emission of blazars is still not figured out definitely, but their spectral energy distributions are well studied observationally. For nearby sources, they consist of two wide bumps: the low-energy one is due to the synchrotron radiation of relativistic electrons while the high-energy one is probably related to the inverse Compton scattering. In the frameworks of a particular EBL model, it is possible to reconstruct the emitted gamma-ray spectrum of the source by correcting the observed spectrum for the pair-production suppression. These “deabsorbed” spectra of distant sources often exhibit hardening, or upward breaks, not seen in spectra of relatively nearby blazars.

For individual sources, spectral hardenings at high energies have been found in many cases (see e.g. Ref. \cite{12}). But the most serious arguments in favour of the anomalous transparency of the Universe come from studies of ensembles of distant sources. Indeed, it was found that the energies corresponding to upward breaks in deabsorbed spectra of blazars change with redshift and always correspond to the energy at which the absorption becomes important (Ref. \cite{18}, a sample of 7 blazars with redshifts $z \lesssim 0.536$ observed by imaging atmospheric Cerenkov telescopes (IACTs) at optical depths $\tau > 1$, IACTs and FERMI LAT, $z \lesssim 2.156$). These effects are surprising because physically, closely and distant blazars are very similar.

Statistical significance of these results is determined by the probability that a similar or stronger effect may be obtained from a fluctuation in a random data set. This probability is often expressed in terms of standard deviations $\sigma$, which however have straightforward interpretation for the Gaussian distribution only. Stated in this way, the significance of the redshift dependence of the break position \cite{18} is $4.2\sigma$, while that of the redshift dependence of the break strength \cite{19} is $12.4\sigma$. These significance estimates are based on statistical analyses only while the results may be subject to systematic uncertainties. For instance, Ref. \cite{18} demonstrates that, under the worst assumptions about systematic errors, the quoted significance of the effect is reduced by $\sim 1.6\sigma$. However, a detailed quantitative study of systematic uncertainties cannot be performed without a complete sample of sources. Indeed, IACTs have narrow field of view and the choice of objects to be observed is determined by humans, not derived from a uniform sample.

A solution to the problem of the unphysical spectral hardenings requires a reduction of the gamma-ray attenuation by means of some mechanism. But the physics behind the usual deabsorption procedure is standard and the assumptions about the photon background are very conservative. One concludes that only new physics or astrophysics may explain the effect.

The only astrophysical explanation was suggested in Ref. \cite{20}. It assumes that the very same gamma-ray blazars produce also a sufficient amount of ultra-high-energy cosmic protons. Interactions of the protons on their way from the source to the Earth result in secondary photons which need a shorter way to reach the observer. Protons are charged, and their trajectories are bend in magnetic fields. Unless extragalactic magnetic fields are as low as $\lesssim 10^{-17}$ G everywhere along the line of sight (including potentially crossed clusters and filaments), this scenario may have tensions with the observation of VHE variability of 4C+21.35 at the timescale of hours \cite{21}.

### 3. ALP EXPLANATIONS

The best-elaborated new-physics explanation involves ALPs (another possibility is to assume violation of the Lorentz invariance which may affect the pair-production cross section). An ALP should mix with photons in external magnetic fields \cite{22, 23}, and
this mechanism allows to suppress the attenuation due to pair production. ALPs do not produce pairs, and gamma-ray photons may convert to ALPs, then travel without attenuation and at some moment convert back to photons. The photon beam is attenuated, but the ALP beam is not and the overall flux suppression is less severe.

For estimates of the probability of conversion in various astrophysical environments, we follow Ref. [24]. The notations we use are determined by the following ALP-photon Lagrangian,

\[ \mathcal{L} = \frac{1}{2} \left( \partial_{\mu} a \partial^{\mu} a - m^2 a^2 \right) - \frac{1}{4} \frac{a}{M} F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}, \]

where \( F^{\mu\nu} \) is the electromagnetic stress tensor and \( \tilde{F}_{\mu\nu} = \epsilon_{\mu\nu\rho\sigma} F^{\rho\sigma} \) is its dual and \( a \) denotes the ALP. The photon/ALP mixing in the magnetic field is determined by the \( F_{\mu\nu} \tilde{F}^{\mu\nu} \) term (photon components with different polarizations mix also): \( g_{a\gamma\gamma} \equiv 1/M \).

Suppose that photons propagate through a region of constant magnetic field. Then the probability to detect an ALP at the distance \( L \) for the pure-photon initial beam is

\[ P = \frac{4 \Delta^2_M}{(\Delta_p + \Delta_{Q,\perp} - \Delta_m)^2 + 4 \Delta^2_M} \sin^2 \left( \frac{1}{2} L \Delta_{osc} \right), \]

where

\[ \Delta^2_{osc} = (\Delta_p + \Delta_{Q,\perp} - \Delta_m)^2 + 4 \Delta^2_M \]

and we used the following notations,

\[ \Delta_M = \frac{B}{2M} = 540 \left( \frac{B}{1 \text{ G}} \right) \left( \frac{10^{10} \text{ GeV}}{M} \right) \text{ pc}^{-1}, \]
\[ \Delta_m = \frac{m^2}{2 \omega} = 7.8 \times 10^{-5} \left( \frac{m_e}{10^{-7} \text{ eV}} \right)^2 \left( \frac{1 \text{ TeV}}{\omega} \right) \text{ pc}^{-1}, \]
\[ \Delta_p = \frac{\omega_p}{2 \omega} = 11 \left( \frac{n_e}{10^{11} \text{ cm}^{-3}} \right) \left( \frac{1 \text{ TeV}}{\omega} \right) \text{ pc}^{-1}, \]

\( \omega \) is the photon (ALP) energy, \( \omega^2 = 4\pi c n_e/m_e \) is the plasma frequency squared, \( n_e \) is the electron density, \( B \) is the magnetic-field component perpendicular to the beam, \( m_e \) is the electron mass and \( \alpha \) is the fine-structure constant.

The remaining notation in Eq. (2) is

\[ \Delta_{Q,\parallel(\perp)} = \frac{m^2_{\gamma,\parallel(\perp)}}{2 \omega}, \]

where \( m^2_{\gamma,\parallel(\perp)} \) is the effective mass square of the longitudinal (transverse) photon due to interaction with the external magnetic field in QED. The critical parameter here is

\[ \kappa = \frac{1}{m_e} \sqrt{\frac{e F_{\mu\nu} l_\nu}{2 \omega}} = \frac{\omega}{m_e} \frac{B_\parallel}{B_{cr}} \approx 4.4 \times 10^{-8} \left( \frac{\omega}{1 \text{ TeV}} \right) \left( \frac{B}{1 \text{ G}} \right), \]

where \( l_\nu \) is the photon 4-momentum and \( B_{cr} = m_e^2/e \approx 4.4 \times 10^{13} \text{ G} \). For \( \kappa \ll 1 \),

\[ \Delta_{Q,\parallel(\perp)} = -1.43 \times 10^4 \left( \frac{\omega}{1 \text{ TeV}} \right) \left( \frac{B}{1 \text{ G}} \right)^2 \text{ pc}^{-1} \]

(see Ref. [24] for general \( \kappa \)).

The strong mixing happens whenever

\[ 4 \Delta^2_M \gg (\Delta_p + \Delta_{Q,\perp} - \Delta_m)^2, \]

which, banning fine-tuned cancellations, means \( \Delta_m \ll 2 \Delta_M \), \( \Delta_p \ll 2 \Delta_M \) and \( |\Delta_{Q,\perp}| \ll 2 \Delta_M \), that is

\[ \omega \gg 700 \text{ keV} \left( \frac{m}{10^{-7} \text{ eV}} \right)^2 \left( \frac{B}{G} \right)^{-1} \left( \frac{10^{10} \text{ GeV}}{M} \right), \]
\[ n_e \ll 10^{13} \text{ cm}^{-3} \left( \frac{\omega}{1 \text{ TeV}} \right) \left( \frac{B}{G} \right), \]
\[ \omega \ll 75 \text{ GeV} \left( \frac{B}{G} \right)^{-1} \left( \frac{M}{10^{10} \text{ GeV}} \right)^{-1} \]

(the latter inequality assumes \( \kappa \ll 1 \)). In addition, the size \( L \) of the magnetic-field region should exceed the oscillation length, \( L \gtrsim \frac{\omega}{\Delta_{osc}} \), which translates into

\[ L \gtrsim 5.8 \times 10^{-3} \text{ pc} \left( \frac{B}{G} \right)^{-1} \left( \frac{M}{10^{10} \text{ GeV}} \right). \]

4. PARAMETERS: TWO SCENARIOS

Two particular scenarios involving ALPs have been proposed to reduce the opacity of the Universe for TeV gamma rays from blazars.

The first one implies intergalactic magnetic fields strong enough to satisfy conditions for efficient ALP/photon mixing all along the path between the source and the observer. This mechanism was first proposed in Ref. [25] in a different context and invoked for the TeV blazar spectra in Ref. [26]. The photon/ALP mixed beam propagates through the Universe in this case and, since the photons are attenuated while ALPs are not, the effective suppression of the flux is smaller compared to the pure-photon case. One can easily derive that, for propagation through domains of randomly oriented magnetic fields, the optical depth is effectively reduced by 2/3 in the long-distance limit. A more detailed recent study [27] results in the following constraints on the relevant ALP parameters: \( m \lesssim 10^{-9} \text{ eV} \) and the ALP-photon coupling \( g_{a\gamma\gamma} \) is
determined from $\xi \equiv (B/\mu G)(g_{a\gamma\gamma} \times 10^{11} \text{ GeV}) \gtrsim 0.3$, that is $g_{a\gamma\gamma} \gtrsim 3 \times 10^{-12} \text{ GeV}^{-1}$.

In the frameworks of the second approach, quite strong magnetic fields are assumed in the source and around the observer, while throughout the way, fields are too weak for ALP/photon mixing. Therefore, the ALP/photon conversion is efficient in the blazar itself and in the Milky Way [25]. Alternatively, it may happen in the galaxy clusters or filaments surrounding the source and/or the observer [24] (see also a more detailed subsequent study in Ref. [28]). In this case, a part of emitted photons is converted to ALPs and then travel intact to the vicinity of the observer, while remaining photons attenuate in a usual way. In the Milky Way, a part of ALPs convert back to photons, which are observed. In this way, the flux suppression (i.e., the effective opacity) does not depend on the distance to the source for large distances. A detailed study of this mechanism is presented, e.g., in Ref. [20] (it is called “the general-source” scenario there). Note that $g_{a\gamma\gamma} \gtrsim 2 \times 10^{-11} \text{ GeV}^{-1}$ is required in this scenario because for lower values of the coupling, the path of the ALP-photon beam through the magnetic field would be too short for efficient conversion even in the maximal-mixing case.

Figure 1 presents the ALP parameter space with present experimental and observational constraints. Regions relevant for the two scenarios discussed above are denoted as “galactic” and “intergalactic”, respectively. Benchmark parameter values for both scenarios are shown by crosses in Fig. 1 (for $m = 10^{-7}$ eV, $g_{a\gamma\gamma} = 10^{-10.4} \text{ GeV}^{-1}$ and $m = 10^{-10}$ eV, $g_{a\gamma\gamma} = 10^{-11.4} \text{ GeV}^{-1}$ [2]). Note that for the “galactic” scenario, $g_{a\gamma\gamma}$ fits well the explanation of anomalous cooling of horizontal-branch stars [32], $g_{a\gamma\gamma} = (0.45 \pm 0.12) \times 10^{-10} \text{ GeV}^{-1}$, see e.g. Ref. [36] for a recent review.

Presently, strict upper bounds on the intergalactic magnetic fields [37] together with the SN1987A constraints [33] start to disfavour the intergalactic-mixing scenario, while some weak evidence for the Galactic anisotropy in the distribution of distant gamma-ray blazars over the sky [25, 38] and persistence of the pair-production anomaly up to high redshifts [19] start to favour the Galactic-mixing model. Future astrophysical studies will be able to distinguish between the scenarios [35].

One more approach to the search for ALP signatures, or to constraining ALP parameters, is based on the expected turbulence of cosmic magnetic fields, which under certain conditions may result in dips and bumps in the spectra of gamma-ray sources residing, e.g., in galaxy clusters. Two studies, based on HESS [39] and FERMI-LAT [40] observations of powerful gamma-ray emitting sources in clusters reported non-observation of these spectral irregularities and therefore claimed the exclusion of certain regions in the ALP parameter space, overlapping with those relevant for the Galactic scenario. However, the magnetic fields in the corresponding clusters were never measured, and the exclusions are based on assumed magnetic-field models. Addition, for instance, of a regular magnetic-field component, which one might expect to present in the vicinity of a powerful active galaxy, would change the results completely. A safer way to search for the spectral irregularities is to use Galactic sources and to invoke models of the Galactic magnetic field which, though uncertain, are at least based on observations. Preliminary results of a study of this kind, reported in Ref. [31], might even favour the existence of an ALP with parameters relevant for the Galactic mixing scenario.

\[1\] For the “galactic” benchmark, the photon/ALP conversion also explains the puzzling BL Lac/cosmic ray correlations observed in HiRes data [34, 35].
5. FUTURE

Future gamma-ray observations will help to verify the existence of the anomalous transparency of the Universe for gamma rays and to further narrow the parameter space of relevant ALPs. They will include, in particular:

(i) high-statistics measurements of spectral energy distributions of relatively nearby blazars at the energies where the expected opacity is large, that is at energies $\sim (50 - 100)$ TeV;

(ii) observation of very distant sources, for which the absorption becomes important at $\sim (10 - 100)$ GeV;

(iii) complete full-sky surveys of distant gamma-ray sources which may reveal or exclude clear patterns of the Galactic anisotropy.

The goal (i) may be achieved with extensive-air-shower arrays equipped with muon detectors, notably Carpet-2+ [22], TAIGA [43] and LHAASO [44]. To reach the goal (i), one would need to employ low-threshold high-altitude Cerenkov telescopes [45]; presently, the project of the Atmospheric Low-Energy Gamma-Ray Observatory (ALEGRO) is proposed which may reside either in Atacama, Chile, or at the Mount Elbrus, Russia (within the Elbrus Gamma-ray Observatory, EGO). The goal (iii) may be realized with future survey-mode data of the Cerenkov Telescope Array (CTA) [46], but the use of the FERMI-LAT data may help as well.

The Any Light Particle Search experiment in its proposed upgraded configuration (ALPS-II) [47] may probe the strongest values of $g_{a\gamma\gamma}$ relevant for the Galactic mixing scenario. Both the Galactic and intergalactic scenarios correspond to the discovery region of the International Axion Observatory (IAXO) [48,49]. For the slightly favoured Galactic case, the number of events in IAXO would allow for a detailed study of the ALP by means of change of the magnetic-field geometry. In fact, even a smaller instrument would be able to discover the ALP in this case.

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