# Searching for axion-like-particles in the sky

C. Burrage[a]*

[a]Theory Group, Deutsches Elektronen-Synchrotron DESY, D-22603 Hamburg, Germany

If dark energy couples to the fields of the standard model we can hope to detect or constrain it through non-gravitational effects. If the dark energy field couples to photons it behaves as an Axion-Like-Particle (ALP). ALPs mix with photons in the presence of magnetic fields and hence affect astronomical observations. We show that empirically established luminosity relations can be used as a new test for ALPs and that when applied to observations of active galactic nuclei this is highly suggestive of the existence of a very light ALP.

DESY 09-080

## 1. Introduction

The remarkable observation that the expansion of the universe is accelerating has lead to a wide variety of possible theoretical explanations. Amongst such models it is common to suppose that the acceleration is driven by a new light scalar ‘quintessence’ field which permeates the universe. If such a new scalar field exists we might naively expect it to couple to the fields of the standard model. Such a coupling would give rise to a new fifth force mediated by the scalar field and provide new decay modes for standard model particles. It is a challenge to quintessence models to explain why such effects should be suppressed. However a coupling between dark energy and the standard model would mean that dark energy could be constrained, or detected, by new non-gravitational effects.

In this article I will focus on the possibility of a coupling between the scalar field and photons. Fields with such couplings are generically known as Axion-Like-Particles (ALPs), in analogy with the properties of axions. Axions are pseudo-scalar particles first proposed in 1977 to solve the strong CP problem of QCD [1,2]. The mass of an axion is proportional to the strength of its coupling, and the allowed Lagrangian terms for axions include a coupling to photons:

$$\mathcal{L} \supset \frac{\phi}{4M}\epsilon_{\mu\nu\lambda\rho}F^{\mu\nu}F^{\lambda\rho} = -\frac{\phi}{M}\mathbf{E}\cdot\mathbf{B}. \qquad (1)$$

We therefore define an axion-like-particle to be any scalar or pseudo-scalar field with a coupling to two photons where, instead of (1), a scalar ALP has the following interaction term

$$\mathcal{L} \supset \frac{\phi}{4M}F_{\mu\nu}F^{\mu\nu} = \frac{\phi}{2M}(\mathbf{B}^2 - \mathbf{E}^2). \qquad (2)$$

We no longer demand any relationship between mass and coupling; $m_\phi$ and $M$ are treated as free parameters to be constrained.

There are a number of dark energy candidates which behave as axion-like-particles. In coupled quintessence models [3] a light scalar fields couples weakly to the fields of the standard model. There are also axionic dark energy models [4,5] in which the dark energy field is a pseudo-scalar. The chameleon model of dark energy allows a scalar field to couple strongly to the standard model fields [6–8], without violating fifth force constraints because, through self interactions, the field acquires a density dependent mass. The properties of a universal chameleon field evolve with the universe and at late times it behaves as quintessence.

As no axion-like-particle has been observed, any model including such fields is constrained

*I would like to acknowledge support from the German Science Foundation (DFG) under the Collaborative Research Centre (SFB) 676.

by the results of experiments. In this article we will be interested in ALPs with masses $m_\phi \lesssim 10^{-12}$ eV, and the constraints on the couplings of such light particles are: For scalar ALPs, $10^{26}$ GeV $< M$, from laboratory constraints on fifth forces and weak equivalence principle violation [9]. For pseudo-scalar ALPs, $10^{11}$ GeV $\lesssim M$, from observations of the neutrino burst from SN 1987A [10]. For chameleonic ALPs, $10^9$ GeV $\lesssim M$, from observations of the polarization of starlight [11].

In the following section I will review the mixing of axion-like-particles and photons in the presence of magnetic fields. In Section 3 I discuss how this could affect astronomical observations, focusing on environments in which the mixing is strongest. I describe, in Section 4, a new test for axion-like-particles which looks for their effects in the empirically established relations between the high and low energy luminosities of certain astrophysical sources. In Section 5 I show that when applied to observations of active galactic nuclei this gives results highly suggestive of the existence of a very light axion-like-particle.

## 2. Optics with ALPs

The couplings (1) and (2) mean that in the presence of a background magnetic field a photon can oscillate into an ALP (and vice versa). The wave equation describing photons and scalars traveling through a magnetic field of strength $B$ oriented orthogonally to the direction of motion of the particles is [12]

$$\left[\omega^2 + \partial_z^2 + \left(\begin{array}{cc} -m_\phi^2 & \frac{B\omega}{M} \\ \frac{B\omega}{M} & -\omega_P^2 \end{array}\right)\right]\left(\begin{array}{c} \phi \\ A_\perp \end{array}\right) = 0, \quad (3)$$

$$\left[\omega^2 - \omega_P^2 + \partial_z^2\right] A_\parallel = 0, \quad (4)$$

where $A_\perp$ and $A_\parallel$ are the components of the photon polarized perpendicular and parallel to the magnetic field. The wave equation for pseudo-scalars is found by interchanging $A_\perp$ and $A_\parallel$ in (3) and (4). $\omega$ is the photon frequency and $\omega_P$ is the plasma frequency, which acts as an effective mass for photons propagating in a plasma. Notice that only one polarization of the photon mixes with the ALP. (3) can be diagonalized and solved to give the mixing matrix

$$\mathcal{M}(z) = U^{-1}\left(\begin{array}{cc} e^{i\Delta_1(z)} & 0 \\ 0 & e^{-i\Delta_2(z)} \end{array}\right) U, \quad (5)$$

where $\Delta_1(z) = \Delta(z)\cos^2\theta/\cos 2\theta$ and $\Delta_2(z) = \Delta(z)\sin^2\theta/\cos 2\theta$. $\Delta(z) = m_{eff}^2 z/4\omega$, $\tan 2\theta = 2B\omega/Mm_{eff}^2$, $m_{eff}^2 = |m_\phi^2 - \omega_P^2|$ and

$$U = \left(\begin{array}{cc} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{array}\right). \quad (6)$$

Therefore in the presence of a background magnetic field the probability that a suitably polarized photon converts into an ALP is

$$P = \sin^2 2\theta \sin^2\left(\frac{\Delta(z)}{\cos 2\theta}\right). \quad (7)$$

If all other variables are fixed, as the frequency of the light is increased the probability of conversion increases and becomes frequency independent.

The mixing has two effects; photon number is no longer conserved, instead the total number of photons and ALPs is conserved, and the polarization of a light beam is distorted by the mixing of photons and ALPs. These optical effects of ALPs can be searched for directly in the laboratory, however the constraints from such experiments are not yet as stringent as those coming from the astrophysical consequences of ALPs.

## 3. Astronomy with ALPs

Large scale magnetic fields exist in galaxies and galaxy clusters, so we may ask whether it is possible to use astronomy to search for ALPs? To model the effects of ALPs on photons passing through astronomical magnetic fields we must take into account the variations in the magnetic field which occur on many different scales. In what follows it will be sufficient to describe the magnetic field as being made up of cells; within each cell the magnetic field is constant and its magnitude is the same in all cells but its orientation varies randomly. Astronomical magnetic fields are often weaker than those that can be created in the laboratory, however for ALP-photon mixing this is compensated for by their much greater extent.

If an astronomical source is observed through such a magnetic field photon-ALP oscillations will affect our observations of both its luminosity and polarization. When this mixing is very strong these effects can be calculated analytically.

### 3.1. Strong mixing

Strong mixing occurs when [11]

$$NP \gg 1, \qquad N\Delta(L) \lesssim \pi/2. \tag{8}$$

$N$ is the number of magnetic domains of length $L$ that are traversed. In the strong mixing limit the probability of mixing becomes large, and almost frequency independent.

In this limit mixing between the ALP and photons fields and between different components of the photon field is so strong that after passing through a large number of randomly oriented magnetic domains the initial flux becomes, on average, equally distributed between $A_1$, $A_2$ and $\phi$ [13], where we now take an arbitrary basis for the photon polarization states. If the initial photon flux is fully polarized the initial state of the system can be written as $\mathbf{u}(0) = (\phi(0), A_1(0), A_2(0))^T$, with $|\mathbf{u}(0)| = 1$, after strong mixing in a large number of domains this evolves to

$$\mathbf{u}_N = (x, \sqrt{1-x^2}\cos\pi\Theta, \sqrt{1-x^2}\sin\pi\Theta)^T, \tag{9}$$

where $x, \Theta \sim U(-1,1)$ [14]. This must be generalized when looking at astronomical sources because there the light emitted is typically partially polarized or unpolarized. A partially polarized state can be written as a superposition of two polarized states each of which evolves according to (8). Then if the initial flux of photons is $I_0$ of which a fraction $p_0$ is polarized the final flux of photons after strong mixing is

$$I_{obs} = \left[1 - (1+p_0)x^2/2 - (1-p_0)y^2/2\right] I_0 \tag{10}$$

where $x, y \sim U(-1,1)$. We define $C = I_{obs}/I_0$ to be the fraction of photons that survive. Then from (10) the probability distribution function for $C$ is

$$f_C(c;p_0) = \frac{1}{\sqrt{1-p_0^2}} \times \left[\tan^{-1}\left(\sqrt{a}\left(1-\frac{2c_+}{1+p_0}\right)^{-1/2}\right) - \tan^{-1}\left(\sqrt{a}\left(1-\frac{2c_-}{1-p_0}\right)^{1/2}\right)\right], \tag{11}$$

where $a = (1+p_0)/(1-p_0)$ and $c_\pm = \min\,(c, (1 \pm p_0)/2)$. The probability distribution is plotted for various initial polarization fractions in Fig. 1.

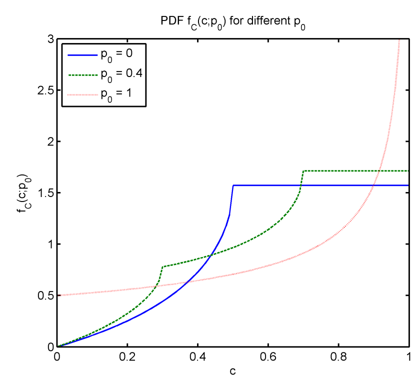



Figure 1. The probability distribution for the attenuation of light which undergoes strong mixing with ALPs plotted for different initial polarization fractions.

The possibility that a large fraction of high energy photons from astronomical sources could convert into ALPs has been used to explain a number of observations of anomalously high fluxes of high energy photons [15,16]. Photons of such high energy are expected to be highly attenuated in the intergalactic medium because they interact with background CMB photons and pair produce. However if photons convert into ALPs in magnetic fields close to their source these ALPs can travel relatively unimpeded through the intergalactic medium and then convert back into photons in the magnetic field of the Milky Way resulting in a higher that expected flux of high energy photons.

## 4. A new test for ALPs

The predicted distribution of the luminosity of astronomical sources whose light mixes strongly with ALPs (11) can be used to test ALP models. As we do not generally know the expected high energy flux of astronomical objects, we need a relation that links the high frequency flux to some other measurable property of the object which is not affected by ALP-photon strong mixing. For a number of compact objects relationships have been empirically established between the high frequency luminosity of a class of objects and their low frequency luminosity. Light at low frequencies mixes only weakly with ALPs and so this luminosity is not altered at leading order. The luminosity relations take the form

$$\log_{10} Y_i = a + b \log_{10} X_i + S_i, \tag{12}$$

where $Y_i$ is the high energy luminosity, and $X_i$ the low energy luminosity, of the $i$-th object. The $S_i$ represent the scatter of individual measurements, It is standard to model the scatter as being normally distributed; $S_i = \sigma\delta_i$ where $\delta \sim N(0,1)$. If the high frequency light has been strongly mixed with ALPs we expect instead

$$S_i = \sigma\delta_i - \log_{10} C_i + \mu, \tag{13}$$

where $\mu$, which is included so that the $S_i$ still have zero mean, can be absorbed in a redefinition of $a$.

The ALP strong mixing model can be compared against the null hypothesis of Gaussian scatter for a given data set by the likelihood ratio test. Given a set of measurements $\{X_i, Y_i\}$ the likelihood of each model is

$$L_f(a, b, \sigma; p_0) = \prod_i \frac{1}{\sqrt{2\pi}}\sigma \times \int_0^1 e^{-\frac{z_i^2}{2\sigma^2}} f_C(c; p_0) dc, \tag{14}$$

where $z_i = \log_{10} Y_i - a - b \log_{10} X_i - \log_{10}((1 - f) + fc)$. $f = 1$ when the high frequency light is strongly mixed with ALPs, and $f = 0$ when it is not. For each model we fit for $a$, $b$, $\sigma$ by maximizing the likelihood (15). We define

$$r(p_0) = 2 \log\left(\frac{\hat{L}_1(p_0)}{\hat{L}_0}\right), \tag{15}$$

where $\hat{L}$ indicates the model with the most likely values of $a, b, \sigma$. Then as both models are described by the same number of parameters, $r(p_0)$ is equivalent to the Bayesian information criterion. Negative $r(p_0)$ is evidence against ALP strong mixing, and positive $r(p_0)$ is evidence for ALP strong mixing. Conventionally $|r(p_0)| > 6$ is considered strong evidence, and $|r(p_0)| > 10$ is considered very strong evidence.

## 5. Results from active galactic nuclei

We shall consider the possible effects of ALP mixing on photons propagating through the magnetic fields of galaxy clusters. These magnetic fields are chosen because of their great extent and because their properties are well understood [17]. Clusters of galaxies are some of the largest objects in the universe; a typical cluster contains $\sim 10^3$ galaxies in a region $\sim 2$ Mpc in radius. Measurements of the Faraday rotation of radiation from intra-cluster radio sources [17] show the presence of magnetic fields with strength $B \approx 1 - 10\ \mu$G which are coherent over distances $1 - 100$ kpc. Typical electron densities in the diffuse plasma in the intracluster medium are $n_e \sim 10^{-3}$ cm$^{-3}$ corresponding to $\omega_P \sim 10^{-12}$ eV. We assume that light from a typical source in the cluster travels a distance $\approx 0.1 - 1$ Mpc through the intracluster magnetic field, and in order to make the analysis model independent we consider ALPs with masses $m_\phi \lesssim \omega_P$.

Strong, frequency independent mixing occurs when the constraints of (8) are satisfied. For light traveling through the magnetic fields of galaxy clusters this requires $M \lesssim 10^{11}$ GeV, (observationally allowed for pseudo-scalars and chameleonic scalars) and $\omega \gtrsim 3 - 30$ keV. Numerical simulations show that the frequency constraint can be relaxed by an order of magnitude. Therefore if the coupling is sufficiently strong x-ray and $\gamma$-ray light mixes strongly with ALPs in galaxy clusters.

Luminosity relations of the form (12), for which the high frequency luminosity is measured at x- or $\gamma$-ray frequencies, exist for Gamma Ray Bursts (GRBs), Blazars and Active Galactic Nuclei (AGN). AGN are the best objects to use for our analysis because there exists a large number of observations which have relatively low intrinsic scatter. The luminosity relation used relates the 2 keV x-ray luminosity and the 250 nm ($\omega \approx 4.95$ eV) optical luminosity. We use observations of 77 AGN from the COMBO-17 and ROSAT surveys [18], at redshifts $z = 0.061 - 2.54$. The likelihood ratio comparing strong ALP mixing with the null hypothesis of Gaussian scatter is

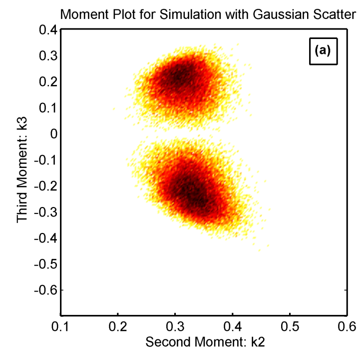
$$r(p_0 \lesssim 0.4) \approx 14. \quad (16)$$

For all $p_0$ we find $r > 11$, but the expectation from AGN physics is that $p_0 < 0.1$ [19]. This is a very strong preference for the ALP strong mixing model over Gaussian scatter. The same analysis applied to the luminosity relations for GRBs and blazars gives, in total, $r \approx 1.6$ [14] which is statistically insignificant.

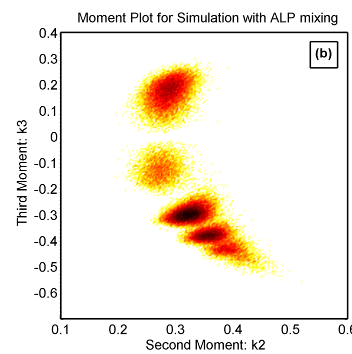
We must ask, however, whether (16) is really evidence for ALP strong mixing, or just that Gaussian scatter was a poor choice for the null hypothesis? This null hypothesis was adopted because for other relations, e.g. those of GRBs and blazars, it provides a good fit to the data. However it may be that a better understanding of the physics of AGN would suggest a better choice for the null hypothesis which could remove the preference for ALP strong mixing. We perform a qualitative check of whether ALP strong mixing is really a good fit to the data by plotting 'fingerprints' of the data. To do this we construct $10^5$ new data sets, of the same size as the original, by bootstrap resampling (with replacement) of the original data set. For each data set we calculate the statistical moments of the distribution

$$k_m(s_i) = \left( \frac{1}{N_p} \sum_i s_i^m \right)^{1/m}, \quad (17)$$

where $s_i = \log_{10} Y_i - (a + b \log_{10} X_i)$. Fingerprints of the data are then histogram plots of $k_i$ vs. $k_j$. We compare these plots with similar fingerprints produced using simulated data for each model. The simulated plots are shown in Fig. 2. The features that distinguish the ALP strong mixing model are a significant asymmetry about the $k_2$ axis and a long 'tail' into the lower right corner of the plot. The equivalent plot for the observations of AGN is shown in Fig. 3. There is a clear qualitative similarity between the plot for the AGN data and the simulated ALP strong mixing plot. Although not shown here this similarity also exists when higher moments of the distribution are plotted.




(a) Best fit Gaussian model [14]




(b) Best fit ALP strong mixing model [14]

Figure 2. Simulated 'fingerprints' (see text for details) comparing the second and third moments of the distribution. Darker regions indicate higher density.

## 6. Conclusions

If a dark energy field couples to photons it behaves as an axion-like-particle. ALPs can mix with photons in the presence of a magnetic field.

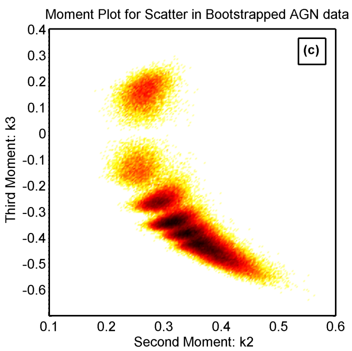



Figure 3. 'Fingerprint' comparing the second and third moments of the distribution of $10^5$ resamplings of the 77 data points of the observed scatter in the AGN $L_x - L_o$ luminosity relation. Darker regions indicate higher density. [14]

This has implications for astronomy as objects are often observed through the magnetic fields of galaxies or galaxy clusters. We have computed the distribution of luminosities expected if light from a class of astronomical sources mixes strongly with ALPs in these magnetic fields. This distribution can be used to constrain the mixing by comparison with empirically established luminosity relations. When applied to observations of active galactic nuclei this is highly suggestive of the existence of a very light ALP over the null hypothesis of Gaussian scatter. In addition we have shown that the distribution of the AGN data displays a strong qualitative similarity to the predictions of the ALP strong mixing model independent of any null hypothesis.

We stress however that the physics behind the luminosity relation is uncertain, and we cannot rule out a more mundane explanation where known physics mimics the effects of ALP strong mixing. An ALP explanation for this effect could be verified, or ruled out, by the proposed International X-ray Observatory (IXO) as if ALP strong mixing occurs a large linear polarization is predicted [11]. Additionally a non-chameleonic ALP with these properties could be detected by future runs of the CERN Axion Solar Telescope (CAST).

## REFERENCES


1. R.D. Pecci and H.R. Quinn, Phys. Rev. Lett. **38** 1440 (1977).
2. R.D. Pecci and H.R. Quinn, Phys. Rev. D. **16** 1791 (1977).
3. L. Amendola, Phys. Rev. D. **62** 043511 (2000).
4. S.M. Carroll, Phys. Rev. Lett. **81** 3067-3070 (1998).
5. J.E. Kim and H.P. Nilles, Phys. Lett. B **553** 1 (2003).
6. J. Khoury and A. Weltman, Phys. Rev. D **69** 044026 (2004).
7. P. Brax, C. van de Bruck, A.-C. Davis, J. Khoury, and A. Weltman, Phys. Rev. D **70** 123518 (2004).
8. P. Brax, C. van de Bruck and A.-C. Davis, Phys. Rev. Lett. **99** 121103 (2007).
9. C. M. Will, Theory and Experiment in Gravitational Physics, Basic Books/Perseus Group, (1993).
10. C. Hagman et al., Axions, Phys. Lett. B. **667** 1 (2008), in: C. Amsler et al. (Particle Data Group).
11. C. Burrage, A.-C. Davis, and Douglas J. Shaw, Phys. Rev. D. **79** 044028 (2009).
12. G. Raffelt and L. Stodolsky, Phys. Rev. D **37** 1237 (1988).
13. C. Csaki, N. Kaloper, and J. Terning, Phys. Rev. Lett. **88** 161302 (2002).
14. C. Burrage, A.-C. Davis and D.J. Shaw, Phys. Rev. Lett. **102** 201101 (2009).
15. M. Fairbairn, T. Rashba and S. Troitsky, (2009) arXiv:0901.4085.
16. M. Roncadelli, A. De Angelis and O. Mansutti, AIP Conf. Proc. 1018 147 (2008).
17. C.L. Carilli and G.B. Taylor , Annu. Rev. Astron. Astrophys. **40** 319 (2002)
18. A.T. Steffen et al., Astron. J. **131** 2826 (2006)
19. S. Chandrasekhar, Radiative Transfer, New York:Dover (1960)