Phenomenology of axion-like particles coupling with photons in the jets of active galactic nuclei

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Abstract. Axions or more generally axion-like particles (ALPs) are pseudo-scalar particles predicted by many extensions of the Standard Model of particle physics (SM) and considered as highly viable candidates for dark matter (DM) in the universe. If they exist in nature, they are expected to couple with photons in the presence of an external magnetic field through a form of the Primakoff effect. In this work, we examine the detectability of signals produced by ALP-photon coupling in the highly magnetized environment of the relativistic jets produced by active galactic nuclei (AGNs). Furthermore, we use the environment of the M87 AGN jet to test a Cosmic ALP Background (CAB) model, motivated by its explanation of the Coma cluster soft X-ray excess. We then demonstrate the potential of the environment of M87 AGN jet to probe low-mass ALP models and to potentially constrain the CAB model proposed to explain the Coma cluster X-ray excess.

1. Introduction

An outstanding result of modern cosmology is that only a small fraction of the total matter content of the universe is made of baryonic matter, while the vast majority is constituted by dark matter (DM) [1]. However, the nature of such a component is still unknown. Light scalar candidates of DM such as axions and axion-like particles (ALPs) are one of the well-motivated hypotheses to explain the nature of DM. Axions [2, 3] are pseudo-Nambu-Goldstone bosons that appear after the spontaneous breaking of the Peccei-Quinn symmetry. These particles were introduced to solve the CP-violation problem of the strong interaction, which represents one of the serious problems in the standard model of particle physics (SM), for a review see reference [4]. The theory, together with observational and experimental bounds, predicts that such axions are very light and weakly interacting with the SM particles, see reference [5]. For these reasons, they are suggested to be suitable candidates for the DM content of the universe [6, 7, 8]. The observation of a light axion would indeed solve the strong CP-problem and at least would participate in improving our understanding of the origin of the component of the DM in the universe. Furthermore, there are plenty of theories beyond the SM that predict the existence of many other pseudo-scalar particles sharing the same phenomenology of the QCD axions [9, 10, 11]. All of this provides strong motivation that axions or now more generally ALPs [12, 13, 14] are a highly viable candidate for DM in the universe.

If they really exist in nature, ALPs are expected to couple with photons in the presence of an external electromagnetic field through the Primakoff effect [15]. This coupling gives rise to the mixing of photons with ALPs [16], which leads to the conversion between photons and ALPs and changes the polarization state of photons. Over the last few years, it has been realized that this phenomenon would allow searches for the ALPs in the observations of distant AGNs in radio galaxies [17, 18]. Since photons emitted by these sources can mix with ALPs during their propagation in the presence of an external magnetic field and this might reduce photon absorption caused by extragalactic background light [19]. Recent observations of blazars by the Fermi Gamma-Ray Space Telescope [20] in the 0.1-300 GeV energy range show a break in their spectra in the 1-10 GeV range. In their paper [21, 22], Mena, Razzaque, and Villaescusa-Navarro have modeled this spectral feature for the flat-spectrum radio quasar 3C454.3 during its November 2010 outburst, assuming that a significant fraction of the gamma rays converts to ALPs in the magnetic fields in and around the large scale jet of this blazar.

The main aim of this work is to follow the approach of [21] to explore the capability of a Cosmic ALP Background (CAB) model to produce the soft X-ray excess in the Coma cluster as claimed in [23]. This test is based upon whether the same model survives scrutiny in highly magnetized AGN jet environments. We find that using the environment of M87 AGN jet and without accounting for misalignment between the AGN jet direction and the line of sight, CAB ALPs conversion into photons would over-produce the X-ray spectrum for the M87 environment. This casts doubt on the existence of a CAB with the necessary properties to explain the observed Coma cluster X-ray excess.

The structure of this paper is as follows. We briefly review the theoretical model that describes the photon-ALP mixing phenomena in section 2 and discuss whether this mixing can explain the soft X-ray excess phenomenon in section 3. The results are shown and discussed in section 4. Finally, a summary and conclusion are provided in section 5.

2. ALPs-photon coupling model

The coupling of ALPs with photons in the presence of an external magnetic field $\mathbf{B}$ is represented by the following Lagrangian [15, 16, 24]

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

where $g_{a\gamma}$ is the ALP-photon coupling constant, $\mathrm{F}_{\mu\nu}$ and $\tilde{\mathrm{F}}^{\mu\nu}$ represent the electromagnetic field tensor and its dual respectively, and a donates the ALP field. While $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic fields respectively. The evolution equations that describe the coupling of ALPs with a monochromatic and linearly polarized photon beam of energy ω propagating along the z-direction in the presence of an external and homogeneous magnetic field transverse $\mathbf{B}_T$ to the beam direction (i.e. in the x-y plane), takes the form [16, 17, 21, 22]

$$i\frac{d}{dz}\begin{pmatrix} A_\perp(z) \\ A_\parallel(z) \\ a(z) \end{pmatrix} = -\begin{pmatrix} \Delta_\perp \cos^2\xi + \Delta_\parallel \sin^2\xi & \cos\xi\sin\xi(\Delta_\parallel + \Delta_\perp) & \Delta_{a\gamma}\sin\xi \\ \cos\xi\sin\xi(\Delta_\parallel + \Delta_\perp) & \Delta_\perp \sin^2\xi + \Delta_\parallel \cos^2\xi & \Delta_{a\gamma}\cos\xi \\ \Delta_{a\gamma}\sin\xi & \Delta_{a\gamma}\cos\xi & \Delta_a \end{pmatrix}\begin{pmatrix} A_\perp(z) \\ A_\parallel(z) \\ a(z) \end{pmatrix} \,, \tag{2}$$

where $A_\perp$ and $A_\parallel$ are the photon linear polarization amplitudes along the x and y axis, respectively, and $a(z)$ donates the amplitude of ALPs. The parameter ξ represents the angle between the transverse magnetic field B_T and a fixed y-axis in the x-y plane. For ALP-photon mixing model in the jet of the blazar 3C454.3, Mena and Razzaque in [21] adopted the following transverse magnetic field and electron density profiles

$$\mathbf{B}_T = \phi \left(\frac{R}{10^{18}\mathrm{cm}}\right)^{-1} \mathrm{G}\,, \quad \text{and} \quad n_e = \eta \left(\frac{R}{10^{18}\mathrm{cm}}\right)^{-s} \mathrm{cm}^{-3}\,, \tag{3}$$

where R is the radius from a central supermassive black hole, believed to be at the center of the AGN. The normalization parameters ϕ and η are found in [21] by fitting GeV γ-ray data with this ALP-photon mixing model for different values of $s = 1, 2$ and 3 corresponding to different electron density profiles. The other different terms of the model, following references [17, 21, 22], are given as

$$\begin{aligned}
\Delta_\perp &\equiv 2\Delta_{\rm QED} + \Delta_{\rm pl}\,, \qquad \Delta_\parallel \equiv (7/2)\Delta_{\rm QED} + \Delta_{\rm pl}\,,\\
\Delta_{\rm QED} &\simeq 1.34\cdot 10^{-18}\phi^2 \left(\frac{\omega}{\rm GeV}\right)\left(\frac{R}{10^{18}{\rm cm}}\right)^{-2}{\rm cm}^{-1}\,,\\
\Delta_{\rm pl} &\simeq -3.49\cdot 10^{-26}\eta \left(\frac{\omega}{\rm GeV}\right)^{-1}\left(\frac{R}{10^{18}{\rm cm}}\right)^{-s}{\rm cm}^{-1}\,,\\
\Delta_{a\gamma} &\simeq 1.50\cdot 10^{-17}\phi \left(\frac{g_{a\gamma}}{10^{-10}{\rm GeV}^{-1}}\right)\left(\frac{R}{10^{18}{\rm cm}}\right)^{-1}{\rm cm}^{-1}\,,\\
\Delta_a &\simeq -2.53\cdot 10^{-19} \left(\frac{\omega}{\rm GeV}\right)^{-1}\left(\frac{m_a}{10^{-7}{\rm eV}}\right)^{2}{\rm cm}^{-1}\,.
\end{aligned} \tag{4}$$

Using this set of parameters, the evolution equations (2) can be numerically solved to find the two components of the photon linear polarization; $A_\perp$ and $A_\parallel$. Then the spectrum for a given blazar can be modified by a normalized suppression factor defined as

$$S(E) = |A_\parallel(E)|^2 + |A_\perp(E)|^2\,. \tag{5}$$

Then the ALP-photon mixing model able to produce a simulation for the γ-ray energy spectra ($\nu F_\nu \equiv E^2 dN/dE$) as a function of the energy of the photons with $\omega \equiv E(1+z)$ where z is the blazar's redshift. In the case of replicating [21] we note that the γ-ray energy spectra read

$$E^2 dN/dE = C E^{-\Gamma+2} S(E)\,. \tag{6}$$

Here, C and Γ are spectral parameters. Hence, the ALP-photon mixing for the blazar jet model includes six free parameters: the normalization for the magnetic field ϕ, the normalization for the electron density η, the ALP mass m_a, the ALP-photon coupling constant $g_{a\gamma}$, and two spectral parameters C and Γ.

3. Cosmic Axion Background

In [25], the authors motivate the existence of a homogeneous CAB arising via the decay of string theory moduli in the very early universe. The suggestion being that the natural energy for such a background lies between 0.1 and 1 keV. Furthermore, in [26] it was shown that such CAB would have a quasi-thermal energy spectrum with a peak dictated by the mass of the ALP. This CAB is also invoked in [23] to explain the soft X-ray excess on the periphery of the Coma cluster with an ALP mass of 1.1×10^{-13} eV and a coupling to the photon of $g_{a\gamma} = 2\times 10^{-13}$ GeV^{-1}.

In this work, we assume, for convenience, that the CAB has a thermal spectrum with an average energy of $\langle E_a \rangle = 0.15$ keV. Then we normalize the distribution to the typical example quoted in [26]. We use the thermal distribution as an approximation, as the exact shape of the distribution will not substantially affect the conclusions we draw. We can then determine the fraction of CAB ALPs converted into photons within the environment of the M87 AGN jet and use this to determine a resulting photon flux. This flux can be compared to X-ray measurements to see if such environments can constrain low-mass ALPs and put limits on the ALP explanation of the Coma X-ray excess.

4. Results and discussion

The Fermi Large Area Telescope in the period from 2010 September 1st to December 13th, reported observations of the radio quasar 3C454.3 at a redshift of z=0.895, constitutes of four epochs [20]: (i) A pre-flare period, (ii) A 13 day long plateau period, (iii) A 5-day flare, and (iv) A post-flare period. The ALP-photon mixing model then has been used in [21] to fit these observation data by plotting the γ-ray energy spectra ($\nu F_\nu \equiv E^2 dN/dE$) as a function of the energy of the photon E to get some constraints on the ALP parameters. To validate the results in [21] , we replicated the model analyses considering the photons to be initially unpolarized, and the following initial condition has been applied: $(A_\parallel(E), A_\perp(E), a(E)) = (\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}, 0)$ at $z \equiv R = 10^{18}$ cm. Besides, the angel ξ has been fixed to be $\pi/4$ during the whole calculations. The evolution equations (2) have been solved numerically to produce the spectral feature of the blazer 3C454.3 in its four epochs for three different cases of the electron profile density.

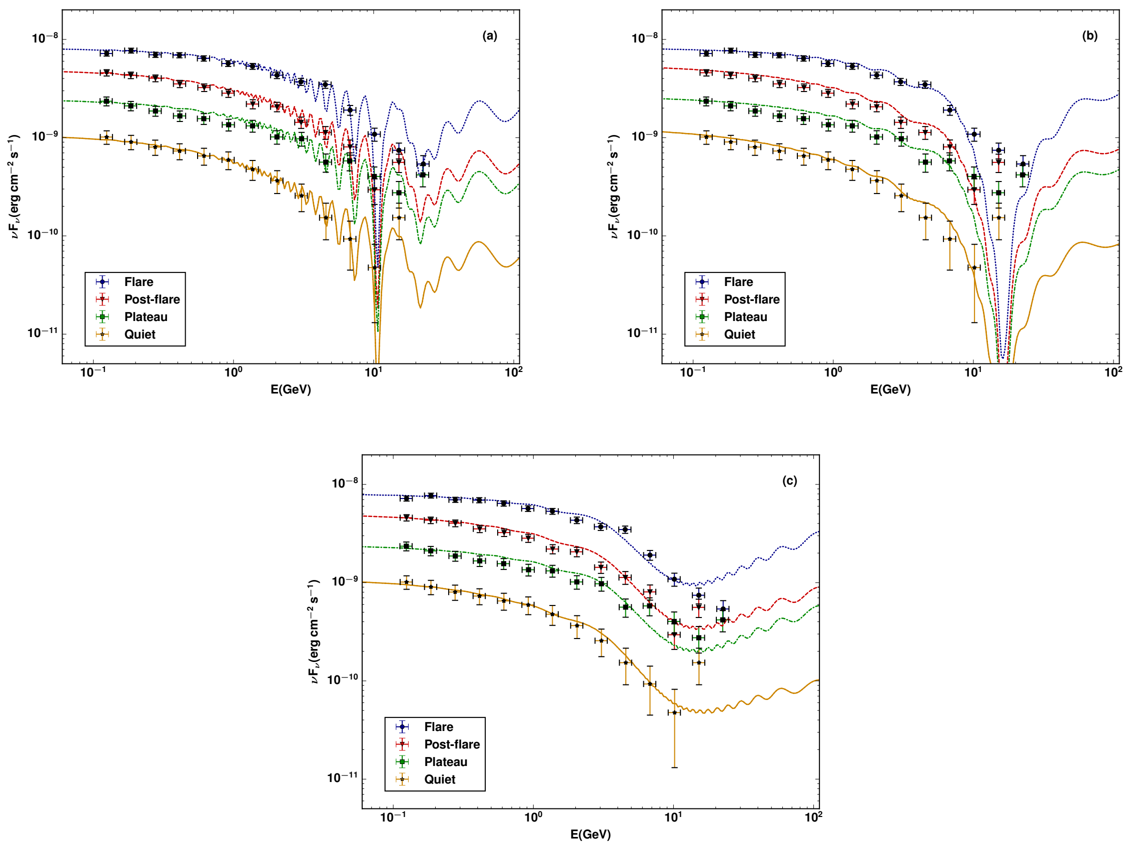

Figure 1. The numerical simulation of the spectral energy fitting observations of blazer 3C454.3 for four different epochs produced using ALP-photon mixing model with electron profile density: (a) $n_e \propto R^{-1}$, (b) $n_e \propto R^{-2}$ and (c) $n_e \propto R^{-3}$.

Figures 1 show the numerical simulation of the spectral energy fitting observations to blazer 3C454.3 for four different epochs (flare, post-flare, plateau, and quiet) using the ALP-photon mixing model with the three different electron density profiles with $s = 1$ (a), 2 (b), and 3 (c). The two spectral parameters C and Γ have been varied from epoch to another as they affected by the γ-ray emission region, while the other four parameters; ϕ, η, m_a, and $g_{a\gamma}$ have been kept fixed. Comparing our results with the one published in [21], allows us to deduce that the spectral energy obtained using the numerical solutions to the evolution equations (2) show a good agreement with these published results. The best fitting of the ALP-photon mixing model for the observation data of blazar jet has been achieved when the transition between photons to

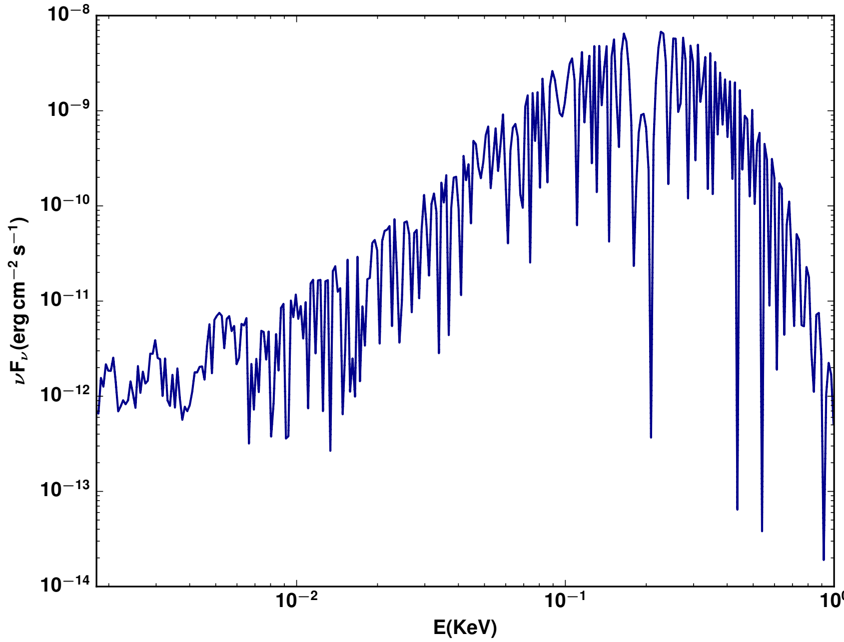

Figure 2. The numerical simulation of the energy spectrum from ALPs conversion to photons in the magnetic field on the jet of M87 AGN.

ALPs take place over different radii, $R \sim 10^{18} - 10^{21}$ cm for $\phi \sim 10^{-2}$, $\eta \sim 10^{9}$, $m_a \sim 10^{-7}$ eV, and $g_{a\gamma} \sim 10^{-10}$ GeV^{-1}.

As a step forward, we apply the ALP-photon mixing model to study the probability of CAB ALPs to convert to photons in the magnetic field on the jet of M87 AGN, which is the best characterized AGN in the literature [29, 30]. We use an electron density profile of the first case with $s = 1$. In addition, we set the ALP mass to be 1.1×10^{-13} eV and the ALP-photon coupling to be $g_{a\gamma} = 2 \times 10^{-13}$ GeV^{-1} in agreement with the models derived in [23] to explain the soft X-ray excess on the periphery of the Coma cluster. The environmental parameters are taken as $\phi = 1.4 \times 10^{-3}$ and $\eta = 0.3$ to make sure that the magnetic field and the electron density profiles used for the M87 AGN are consisted with the obtained values in [27]. Preliminary results are shown in figure 2 for the energy spectrum obtained from the numerical simulation for ALP-photon conversion in the magnetic field of the M87 AGN jet. The resulting photon flux between 0.3 and 8 keV obtained from the simulation is $\sim 2.57 \times 10^{-10}$ erg cm^{-2} s^{-1}. This value is about two orders of magnitude greater than the observed flux $\sim 3.76 \times 10^{-12}$ erg cm^{-2} s^{-1} from the M87 AGN in the same energy range [28].

5. Conclusion

In this work, we have examined the ALP-photon model which developed by Mena and Razzaque to fit the spectral features of the flat-spectrum radio quasar 3C454.3 during its November 2010 outburst. This allowed the aforementioned authors to derive constraints on the ALP parameters by assuming that a significant fraction of the gamma rays converts to ALPs in the presence of an external magnetic field in the large scale jet of this blazar. We reproduced their results that have a very good agreement with the observation data for the 3C454.3 blazar. Indeed, this makes us very confident that our simulation is robust. As a step forward, we used the environment of the M87 AGN jet to test whether the CAB ALP conversion to photons which is proposed to explain the Coma cluster X-ray excess, survives comparison with X-ray data in M87. We find that the environment of the M87 AGN jet provides preliminary suggestions of an X-ray over-production around two orders of magnitude. This casts doubt on whether the Coma X-ray excess CAB model is viable in general. Further effects, such as misalignment between the AGN jet direction and the line of sight, must be considered in future work before we can rule out the CAB model proposed to account for the observed Coma X-ray excess.

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References
[1] Komatsu E, Smith K, Dunkley J, Bennett C, Gold B, Hinshaw G, Jarosik N, Larson D, Nolta M, Page L *et al.* 2011 *The Astrophysical Journal Supplement Series* **192** 18
[2] Peccei R D and Quinn H R 1977 *Phys. Rev. Lett.* **38** 1440–1443
[3] Weinberg S 1978 *Physical Review Letters* **40** 223
[4] Peccei R D 2008 *Axions* (Springer) pp 3–17
[5] Asztalos S J, Rosenberg L J, van Bibber K, Sikivie P and Zioutas K 2006 *Annu. Rev. Nucl. Part. Sci.* **56** 293–326
[6] Preskill J, Wise M B and Wilczek F 1983 *Physics Letters B* **120** 127–132
[7] Abbott L F and Sikivie P 1983 *Physics Letters B* **120** 133–136
[8] Dine M and Fischler W 1983 *Physics Letters B* **120** 137–141
[9] Arvanitaki A, Dimopoulos S, Dubovsky S, Kaloper N and March-Russell J 2010 *Physical Review D* **81** 123530
[10] Cicoli M, Goodsell M D and Ringwald A 2012 *Journal of High Energy Physics* **2012** 146
[11] Anselm A and Uraltsev N 1982 *Physics Letters B* **114** 39–41
[12] Arias P, Cadamuro D, Goodsell M, Jaeckel J, Redondo J and Ringwald A 2012 *Journal of Cosmology and Astroparticle Physics* **2012** 013
[13] Ringwald A 2012 *Physics of the Dark Universe* **1** 116–135
[14] Marsh D J 2016 *Physics Reports* **643** 1–79
[15] Sikivie P 1983 *Physical Review Letters* **51** 1415
[16] Raffelt G and Stodolsky L 1988 *Physical Review D* **37** 1237
[17] Bassan N, Mirizzi A and Roncadelli M 2010 *Journal of Cosmology and Astroparticle Physics* **2010** 010
[18] Horns D, Maccione L, Mirizzi A and Roncadelli M 2012 *Physical Review D* **85** 085021
[19] Harris J and Chadwick P M 2014 *Journal of Cosmology and Astroparticle Physics* **2014** 018
[20] Abdo A A, Ackermann M, Ajello M, Allafort A, Baldini L, Ballet J, Barbiellini G, Bastieri D, Bellazzini R, Berenji B *et al.* 2011 *The Astrophysical journal letters* **733** L26
[21] Mena O and Razzaque S 2013 *Journal of Cosmology and Astroparticle Physics* **2013** 023
[22] Mena O, Razzaque S and Villaescusa-Navarro F 2011 *Journal of Cosmology and Astroparticle Physics* **2011** 030
[23] Angus S, Conlon J P, Marsh M D, Powell A J and Witkowski L T 2014 *Journal of Cosmology and Astroparticle Physics* **2014** 026
[24] Anselm A A 1988 *Physical Review D* **37** 2001
[25] Conlon J P and Marsh M D 2013 *Physical review letters* **111** 151301
[26] Conlon J P and Marsh M D 2013 *Journal of High Energy Physics* **2013** 214
[27] Park J, Hada K, Kino M, Nakamura M, Ro H and Trippe S 2019 *The Astrophysical Journal* **871** 257
[28] Donato D, Sambruna R M and Gliozzi M 2004 *ApJ* **617** 915–929 (*Preprint* astro-ph/0408451)
[29] Macchetto F, Marconi A, Axon D J, Capetti A, Sparks W and Crane P 1997 *The Astrophysical Journal* **489** 579
[30] Gebhardt K and Thomas J 2009 *The Astrophysical Journal* **700** 1690