Axion-like Particles as an Effective Magnetic Field in the early universe

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Write abstract here (to be updated after completing the other parts):
This paper explores the interaction of axions with electrons in the early universe, emphasizing the intriguing similarity between the classical Hamiltonian governing the axion field and that proposed by Peter Graham for axion-electron interactions. The study suggests that the axion field may act as an effective magnetic field in the early cosmos, leading to valuable constraints on a specific model of dark matter. The parameter space under investigation involves the mass of Axion-Like Particles (ALPs) and the interaction coefficient of axion-electrons. While the derived constraints do not significantly surpass existing limits from white dwarf observations, the novel approach offers a unique probe for refining our understanding of axions and their potential role as dark matter constituents. The exploration of this uncharted territory opens up new avenues for future experiments and observations to further constrain the parameter space of axion physics.

Keywords: Cosmology: 21-cm, Axions

I. INTRODUCTION

Bib test: [1–4]

II. METHODOLOGY

In this section we derive the relevant formulas which we use to calculate the bounds on the interaction coefficient of electrons and axions. We start with the classical Hamiltonian defined as:

$$H = -\vec{\mu}.\vec{B} \tag{1}$$

where μ is the magnetic moment interacting with an external magnetic field (B) in the Hamiltonian of a system. On the other hand, it is well known that the part of the Hamiltonian for the interaction between the axions and electrons [1] is:

$$H = g_{\text{aee}}(\vec{\nabla}\phi_{\text{a}}.\vec{\sigma}_{\text{e}}) \tag{2}$$

where g_{aee} is the coefficient of axion-electron interactions, ϕ_{a} is the axion field and $\vec{\sigma}_{\text{e}}$ is the spin matrix of the electron.

By combining equations 1,2 one can infer that the gradient of the axion field is equivalent to an effective magnetic field [5]:

$$\overrightarrow{B_{\text{eff}}} = \frac{g_{\text{aee}}}{\mu_{\text{e}}}(\vec{\nabla}\phi) \tag{3}$$

Here I derive a solution similar to [6] but taking into account the variations of the Hubble parameter as well. Assuming the scalar field equation for ALPs:

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2\phi = 0 \tag{4}$$

where m_ϕ is the mass if the axion field. Assuming matter domination the Hubble parameter will be H=2/3t and the above equation will be in this form:

$$\ddot{\phi} + \frac{2}{t}\dot{\phi} + m_\phi^2\phi = 0 \tag{5}$$

The general solution takes a oscillatory function:

$$\phi = \frac{1}{t}(Acos(m_\phi t) + Bsin(m_\phi t)) \tag{6}$$

The energy density and the pressure of the field is:

$$\rho_\phi = \frac{\dot{\phi}^2}{2} + \frac{m_\phi^2\phi^2}{2} \tag{7}$$

$$P_\phi = \frac{\dot{\phi}^2}{2} - \frac{m_\phi^2\phi^2}{2} \tag{8}$$

In the ΛCDM model, the Hubble rate at matter-radiation equality is around $H(a_{\text{eq}}) \approx 10^{-28}$ eV. Axions with a mass surpassing this threshold begins oscillating during the radiation-dominated era and present viable candidates to constitute the entirety of dark matter. [7]. Since the ALPs are constrained to less than 5% of the DM density for masses below 10^{-24} [4], we will assume that $H \ll m$. Hence the density of the field:

$$\rho_\phi \simeq \frac{m^2}{a^3t_0^2}(A^2sin^2(mt) + B^2cos^2(mt)) \tag{9}$$

We can also solve the equation of the field on the perturbation level [4].

$$\ddot{\delta\phi} + 3H\dot{\delta\phi} + (m_\phi^2 + \frac{k^2}{a^2})\delta\phi = 0 \tag{10}$$

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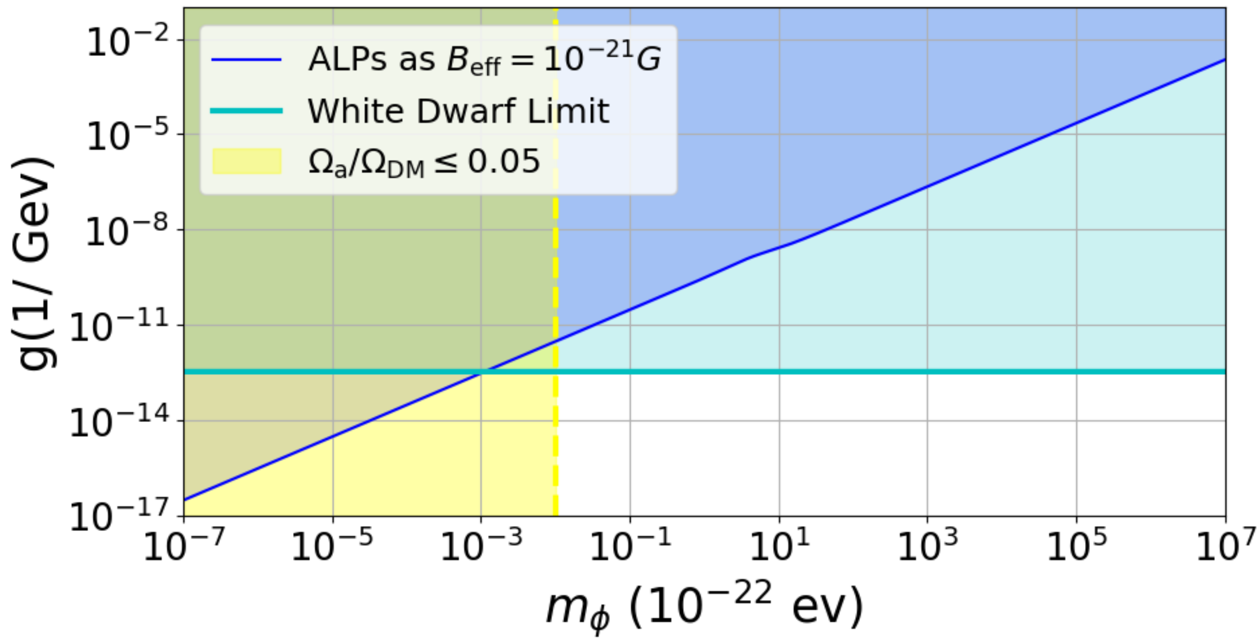

Figure 1. Upper limits on the coupling constant of axion-electron. Other limits from white Dwarfs and WiggleZ survey analysis are shown for comparison.

It can be shown that the term including the wave number is negligible which gives a solution similar to the filed itself:

$$\delta\phi = \frac{1}{t}(Ccos(m_\phi t) + Dsin(m_\phi t)). \tag{11}$$

The perturbed energy density and pressure are [4]:

$$\delta\rho_\phi = \dot{\phi}\dot{\delta\phi} + m^2\phi\delta\phi \tag{12}$$
$$\delta p_\phi = \dot{\phi}\dot{\delta\phi} - m^2\phi\delta\phi \tag{13}$$

and the sound speed defined as:

$$C_a^2 = \frac{\delta p}{\delta\rho} = \frac{(k/4ma)^2}{1 + k/4ma)^2} \tag{14}$$

On the other hand, going to the Fourier Space and using $(\vec{\nabla}\delta\phi)_i = \delta\phi.k_i$ and using equation (11) we have:

$$\vec{B} = \frac{g_a\vec{k}}{\mu_e}(Ccos(m_\phi t) + Dsin(m_\phi t))\frac{a^{\frac{-3}{2}}}{t_0} \tag{15}$$

The initial condition for the axion field is such that it starts to roll slowly

$$\dot{\phi}(0) = 0 \Rightarrow A = 0. \tag{16}$$

Choosing $A = 0$ results in the following equations:

$$\rho_\phi = \frac{m^2}{t^2}B^2cos^2(mt) \tag{17}$$
$$\delta\rho \approx \frac{m^2}{t^2}BD \tag{18}$$
$$\delta = \frac{\delta\rho}{\rho} = \frac{D}{Bcos^2(mt)} \tag{19}$$
$$C_a^2 = \frac{(k/4ma)^2}{1 + (k/4ma)^2} = Cos[2mt] + \frac{C}{D}Sin[2mt]. \tag{20}$$

And density becomes:

$$\rho_\phi = \frac{m^2}{t^2}B^2cos^2(mt) = \frac{4M_p^2\Omega_{DM}}{3t^2} \tag{21}$$
$$D(k) = Bcos^2(mt)\delta = \frac{2M_p}{m}\sqrt{\frac{\Omega_{DM}}{3}}cos(mt)\delta(k). \tag{22}$$

Therefore, we have B as a function of m and D as a function of m,k. Here I use the the following equation and then I use the value of the variance from the CLASS code.

$$\delta(k) = \frac{\delta\rho}{\rho} = \Delta(k) = \sqrt{\frac{k^3P(k)}{2\pi^2}} \tag{23}$$

From (15) we have:

$$g_a = \frac{\mu_e B t_0 a^{\frac{3}{2}}}{k(Ccos(m_\phi t) + Dsin(m_\phi t))}. \tag{24}$$

Therefore the axion field as an effective magnetic field will take this form:

$$B_{\rm eff}(k) = \frac{g_{\rm a}k}{\mu_{\rm e}}\frac{a^{\frac{-3}{2}}}{t_0}\frac{2M_{\rm p}}{m}\sqrt{\frac{\Omega_{\rm DM}}{3}}\delta(k)\times \\ cos(m_\phi t)\left(sin(m_\phi t) + \frac{(k/4ma)^2}{1+(k/4ma)^2}cos(m_\phi t) \right. \\ \left. - \frac{cos(m_\phi t)cos(2m_\phi t)}{sin(2m_\phi t)}\right) \tag{25}$$

Figure 1 shows the upper limits on the coupling constant of axion-electron for $B = 10^{-21}$ G [8, 9] and k=1. Note that in this figure a time average was taken. White Dwarf limits [10–12] on the coupling and also the part of the mass range for which 100% dark matter in the form of ALPs is excluded [4] is showed.

This calculation shows that although considering axions as an effective magnetic field is an interesting approach to the parameter space of axions and their interaction strength with electrons, still lacks the constraining power compared to the pervious bounds.

A. subsection

1. *subsubsection*

B. subsection

C. subsection

1. *subsubsection1*

2. *subsubsection2*

III. RESULTS

IV. CONCLUSIONS

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