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Letter

Electromagnetic waves propagating in the string axiverse

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It is widely believed that axions are ubiquitous in string theory and could be dark matter. The peculiar features of axion dark matter are coherent oscillations and a coupling to the electromagnetic field through the Chern–Simons term. In this letter, we study the consequences of these two features of axions with mass in the range 10^{-13} eV to 10^3 eV. First, we study the parametric resonance of electromagnetic waves induced by the coherent oscillation of the axion. Since the resonance frequency is determined by the mass of the axion dark matter, if we detect this signal, we can get information on the mass of the axion dark matter. Second, we study the velocity of light in the background of the axion dark matter. In the presence of the Chern–Simons term, the dispersion relation is modified and the speed of light will oscillate in time. It turns out that the change in the speed of light would be difficult to observe. We argue that future radio wave observations of the resonance can give rise to a stronger constraint on the coupling constant and/or the density of the axion dark matter.

Subject Index E64, E83

1. *Introduction* According to string theory, axions are ubiquitous in the universe, dubbed the string axiverse [1–5]. Remarkably, axions could be a dark component of the universe and might be a dominant element of dark matter [6–12]. In fact, it is difficult to discriminate between axion dark matter and cold dark matter on large scales. Therefore, it is important to find a method for proving the existence of axions.

The key feature of axion dark matter is its coherent oscillation. In particular, if the axion has a mass of 10^{-23} eV, the time scale of the oscillation is a few years and the oscillation produces an oscillation in the gravitational potential. Hence, one can use pulsar timing arrays to observe oscillating gravitational potential [13–16]. There are other methods proposed for detecting axion dark matter, for example the super-radiance instability of the axion field in rotating black holes constraining the mass range to 10^{-20}–10^{-10} eV [2,17–19], gravitational wave interferometers for probing axions with mass 10^{-22}–10^{-20} eV [20], the dynamical resonance of binary pulsars probing the mass range 10^{-23}–10^{-21} eV [21], and cosmological axion oscillations for exploring a wide mass range [22,23].

Recently, we have studied gravitational waves in dynamical Chern–Simons gravity in the axion dark matter background [24]. We found that there occurs a parametric resonance of gravitational waves with parity violation, that is, circularly polarized gravitational waves that allow us to probe axions in the mass range 10^{-14}–10^{-10} eV.

Apparently, we can expect the same phenomena for electromagnetic waves. Since electromagnetic waves are often used to explore the universe, it is worth studying the phenomena in detail.

The electrodynamics in the presence of the axion is called the axion electrodynamics [25] and has the Chern–Simons coupling between the axion and the gauge field. We see this that interaction induces the parametric resonance of electromagnetic waves and also yields an oscillation of the speed of light in time. In this paper, we study these two effects to give rise to a new way to explore axion dark matter in the mass range 10^{-13}–10^{3} eV corresponding to the observable frequency range of electromagnetic waves of 10Hz–10^5 THz. The lower bound comes from the limit of the observation of the electromagnetic field on Earth by using the Schumann effect, and the upper bound comes from the fact that axions with mass above 10^3 eV are unstable against decaying into photons [9–12].

The organization of the paper is as follows. In Sect. 2, we introduce the axion electrodynamics. In Sect. 3, we derive wave equations in the oscillating axion background. In Sect. 4, we study the parametric resonance in the axion background. In Sect. 5, we investigate the speed of light. The final section is devoted to conclusions.

2. *Axion electrodynamics* The action of the axion electrodynamics is given by

$$S = S_{\rm EM} + S_\Phi + S_{\rm int}, \tag{1}$$

where each part of this action reads

$$\begin{aligned} S_{\rm EM} &\equiv \int dx^4 \sqrt{-g}\left(-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}\right),\\ S_\Phi &\equiv \int dx^4 \sqrt{-g}\left(-\frac{1}{2}\left(\nabla_\mu\Phi\right)\left(\nabla^\mu\Phi\right) - U(\Phi)\right),\\ S_{\rm int} &\equiv \int dx^4 \sqrt{-g}\left(-\frac{\lambda}{4}\Phi F_{\mu\nu}\tilde{F}^{\mu\nu}\right). \end{aligned} \tag{2}$$

Here, λ is a coupling constant, $U(\Phi)$ is a potential function for an axion field Φ, and $A^\mu = (A^0, \boldsymbol{A})$ is a gauge field with field strength $F_{\mu\nu} \equiv \nabla_\mu A_\nu - \nabla_\nu A_\mu$. The dual of the field strength $\tilde{F}^{\mu\nu}$ is defined by

$$\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}, \tag{3}$$

where the antisymmetrical epsilon tensor $\epsilon^{\mu\nu\rho\sigma}$ is given by

$$\epsilon^{\mu\nu\rho\sigma} \equiv \frac{1}{\sqrt{-g}}\tilde{\epsilon}^{\mu\nu\rho\sigma} \quad \text{and} \quad \tilde{\epsilon}^{0123} = +1. \tag{4}$$

Here, $\tilde{\epsilon}^{\mu\nu\rho\sigma}$ is the Levi-Civita symbol.

From the above action, we get the equations of motion for electromagnetic waves:

$$\nabla_\mu F^{\alpha\mu} + \frac{\lambda}{2}\epsilon^{\alpha\mu\nu\lambda}\left(\nabla_\mu\Phi\right)F_{\nu\lambda} = 0 \tag{5}$$

and the equation for the axion field

$$\nabla_\mu\nabla^\mu\Phi - \frac{d}{d\Phi}U(\Phi) = \frac{\lambda}{4}F_{\mu\nu}\tilde{F}^{\mu\nu}. \tag{6}$$

Now we can study electromagnetic wave propagation in the axion background.

3. *Wave equations in the axiverse* We assume the background spacetime is the Minkowski spacetime, because the dynamics of cosmic expansion can be neglected on intergalactic scales [26]. Then, the metric reads

$$\begin{aligned} ds^2 &= \eta_{\mu\nu}\, dx^\mu\, dx^\nu \\ &= -dt^2 + dx^2 + dy^2 + dz^2. \end{aligned} \tag{7}$$

Now, the covariant derivative is simply reduced to a partial derivative ∂_μ. We are interested in the time evolution of the gauge field in the axion background. The gauge field is considered as the perturbed field $A_\mu = \delta A_\mu$. Next, we consider a homogeneous axion background

$$\Phi(t, \boldsymbol{x}) = \Phi(t). \tag{8}$$

Then, the equation of motion of the axion is given by

$$(\partial_t^2 + m^2)\Phi(t) \simeq 0. \tag{9}$$

Here, we assumed the potential of the axion as

$$U(\Phi) = \frac{1}{2} m^2 \Phi^2. \tag{10}$$

In fact, we can neglect the higher-order terms because the amplitude of axion oscillation around the minimum of the potential is much smaller than the axion decay constant. It is easy to obtain the solution

$$\Phi(t) = \Phi_0 \cos(m\,t), \tag{11}$$

where Φ_0 is determined by the density ρ of the dark matter and the mass of the axion m as

$$\Phi_0 = \frac{\sqrt{2\rho}}{m}. \tag{12}$$

The equations of motion of the axion electrodynamics can be deduced as

$$\begin{aligned} \partial_\mu \delta F^{0\mu} &= 0, \\ \partial_\mu \delta F^{i\mu} - \lambda \epsilon^{ijk}\,(\partial_0 \Phi)\, \partial_j \delta A_k &= 0. \end{aligned} \tag{13}$$

Here, the epsilon tensor in this coordinate system is defined as

$$\epsilon^{ijk} \equiv \epsilon^{tijk}. \tag{14}$$

The time component of the modified Maxwell equation is the same as the conventional Maxwell equation.

This modified Maxwell theory is invariant under the gauge transformation

$$A_\mu \to A'_\mu = A_\mu + \partial_\mu \Lambda. \tag{15}$$

So, we can adopt the radiation gauge for the electromagnetic field,

$$\delta A^0 = 0, \quad \nabla \cdot \delta \boldsymbol{A} = 0, \tag{16}$$

and we get the wave equations of axion electrodynamics:

$$\Box\, \delta \boldsymbol{A} + \lambda\,(\partial_0 \Phi)\,(\nabla \times \delta \boldsymbol{A}) = 0, \tag{17}$$

where we defined the derivative operators $\Box \equiv \nabla_\mu \nabla^\mu$ and $\nabla \equiv (\partial_x, \partial_y, \partial_z)$.

We can diagonalize the wave equations with the circular polarization basis. In Fourier space, the vector field $\delta\boldsymbol{A}$ is expressed by

$$\delta\boldsymbol{A}(t,\boldsymbol{x}) \equiv \int \delta\tilde{\boldsymbol{A}}(t)\, e^{i\boldsymbol{k}\cdot\boldsymbol{x}} d\boldsymbol{k}, \tag{18}$$

where $\boldsymbol{k}$ is the wave number vector. The transverse gauge condition can be written as

$$\boldsymbol{k}\cdot\delta\tilde{\boldsymbol{A}}(t) = 0. \tag{19}$$

We can take polarization basis vectors, $\boldsymbol{e}_{(1)},\ \boldsymbol{e}_{(2)}$, satisfying the following conditions:

$$\boldsymbol{e}_{(I)}\cdot\boldsymbol{k} = 0, \tag{20}$$

$$\boldsymbol{e}_{(I)}\cdot\boldsymbol{e}_{(J)} = \delta_{IJ}, \quad \text{for } I, J = (1,2), \tag{21}$$

$$\boldsymbol{e}_{(1)}\times\boldsymbol{e}_{(2)} = \frac{\boldsymbol{k}}{k}. \tag{22}$$

Here, we defined $k = |\boldsymbol{k}|$. Thus, the Fourier coefficient $\delta\tilde{\boldsymbol{A}}(t)$ is expanded as

$$\delta\tilde{\boldsymbol{A}}(t) = \sum_{I=1,2}\delta\tilde{A}_I(t)\boldsymbol{e}_{(I)}. \tag{23}$$

Alternatively, we can use the circular polarization basis

$$\boldsymbol{e}_{\rm R} \equiv \frac{\boldsymbol{e}_{(1)}+i\boldsymbol{e}_{(2)}}{\sqrt{2}} \quad \text{and} \quad \boldsymbol{e}_{\rm L} \equiv \frac{\boldsymbol{e}_{(1)}-i\boldsymbol{e}_{(2)}}{\sqrt{2}}. \tag{24}$$

Now, the Fourier coefficient $\delta\tilde{\boldsymbol{A}}(t)$ is expanded as

$$\delta\tilde{\boldsymbol{A}}(t) = \sum_{B={\rm L,R}}\delta\tilde{A}_B(t)\boldsymbol{e}_B. \tag{25}$$

Note that the components are related as

$$\delta\tilde{A}_{\rm R} = \frac{\delta\tilde{A}_{(1)} - i\,\delta\tilde{A}_{(2)}}{\sqrt{2}}, \quad \delta\tilde{A}_{\rm L} = \frac{\delta\tilde{A}_{(1)} + i\,\delta\tilde{A}_{(2)}}{\sqrt{2}}. \tag{26}$$

This basis is useful for studying parity violation. Using the relation

$$\epsilon^{ijk}\frac{k^j}{k}\boldsymbol{e}^k_{\rm R/L} = \mp i\boldsymbol{e}^i_{\rm R/L} \tag{27}$$

we can diagonalize the wave equations as

$$\partial_t^2\left(\delta\tilde{A}_B\right) + k^2\left(1+\epsilon_B\lambda\frac{m}{k}\Phi_0\sin(mt)\right)\delta\tilde{A}_B = 0 \tag{28}$$

where

$$\epsilon_B = \begin{cases} 1 & : B = {\rm R}, \\ -1 & : B = {\rm L}. \end{cases} \tag{29}$$

Since the axion has a nontrivial profile, parity symmetry is violated in the equation of motion. Thus, circular polarization should be generated. To be more precise, it is useful to define the degree of polarization of the gauge field,

$$\text{parity}(t) \equiv \frac{\left|\delta\tilde{A}_{\rm R}\right|^2 - \left|\delta\tilde{A}_{\rm L}\right|^2}{\left|\delta\tilde{A}_{\rm R}\right|^2 + \left|\delta\tilde{A}_{\rm L}\right|^2}. \tag{30}$$

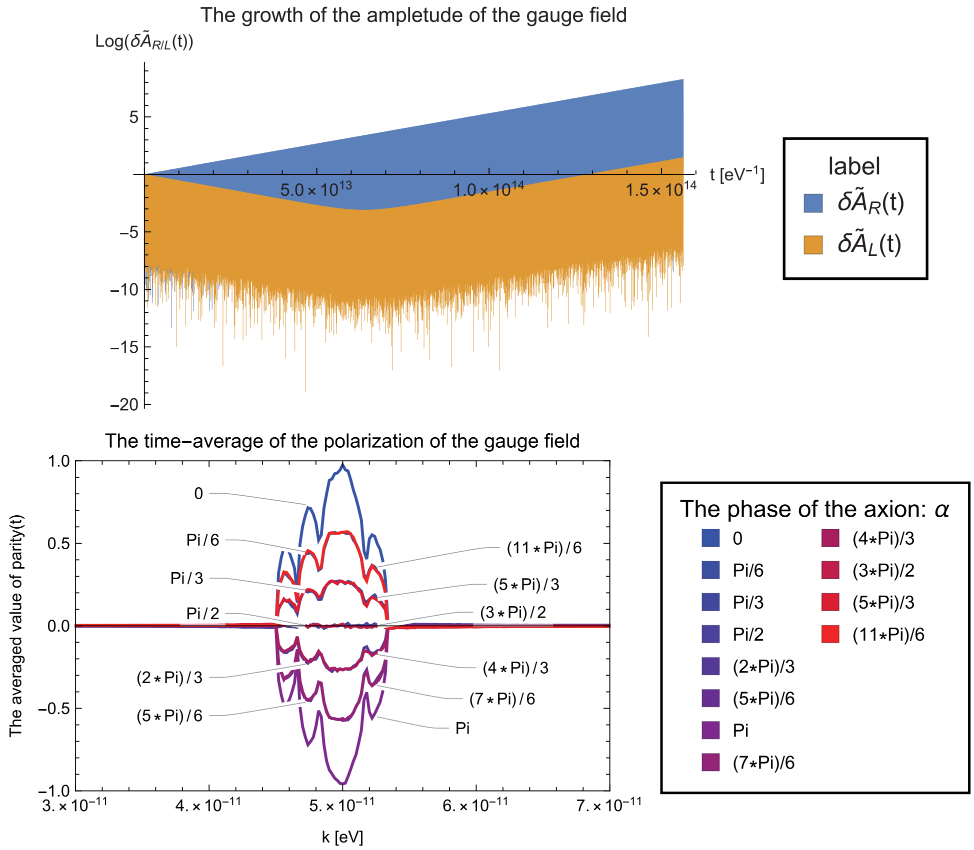

Fig. 1. Plots of the growth of the amplitude of the gauge field, $\delta\tilde{A}_{\mathrm{R/L}}$, and the time average of parity(t). We plotted the figure with $m = 10^{-10}$ eV, $\rho = 0.3 \times 10^6$ GeV cm^{-3}, and $\lambda = \left(10^4\,\mathrm{GeV}\right)^{-1}$ in the range of t from $0\,\mathrm{eV}^{-1}$ to $1.6 \times 10^{14}\,\mathrm{eV}^{-1}$. The axion field could have the freedom of the phase $mt + \alpha$. In the upper plot, we see that the growth of the amplitude for $\alpha = 0$ depends on the chirality. In the lower plot, we calculated the time-averaged circular polarization for various phases α and for various wavenumbers. If we change the phase of the axion field from mt to $mt + \pi$, parity(t) changes sign. If we take the phase $\alpha = \pm\pi/2$, there is no circular polarization. We see that, except for $\alpha = \pm\pi/2$, circular polarization appears. These results show that axion dark matter can produce parity violation in electromagnetic waves.

The axion field could have the freedom of the phase $mt + \alpha$. In Fig. 1, we show the growth of the amplitude of the gauge field for the specific phase of the axion oscillation $\alpha = 0$ and the degree of circular polarization parity(t) for various phases. Since the evolution depends on the chirality, the growth of one of the modes is generically larger than that of the other mode. So, circular polarization appears except for $\alpha = \pm\pi/2$. Moreover, since the dispersion relation is modified by the axion, the speed of light is oscillating. We study the effects of these phenomena on electromagnetic waves in the following.

4. *Parametric resonance* We assume that a lot of clumps whose sizes are about the Jeans length L_{a} exist in the core of Galaxy and the axion is coherently oscillating there. These fuzzy objects have interactions with the electromagnetic fields through the Chern–Simons coupling. Thus, the coherent oscillations of the axion induce the parametric resonance of electromagnetic waves.

First of all, we recall some formulae from the general theory of parametric resonance. The equation of motion of the parametric resonance is given by

$$\ddot{x}(t) + \omega^2\left(1 + \delta\sin(2\omega_0 t)\right)x(t) = 0. \tag{31}$$

Here, we have assumed that the value of δ is sufficiently small. Then, it is known that the resonance frequency is given by

$$\omega = \omega_0, \tag{32}$$

and, at the resonance frequency, the maximal growth rate can be estimated by

$$\Gamma_{\max} \equiv \frac{\omega^2 \delta}{4\omega_0}. \tag{33}$$

Then, the solution of the amplitude is given by

$$x(t) \propto e^{\Gamma_{\max} t}. \tag{34}$$

Finally, the width of the frequency of this resonance is given by

$$\omega_0 - \frac{\omega_0 \delta}{4} \lesssim \omega \lesssim \omega_0 + \frac{\omega_0 \delta}{4}, \tag{35}$$

so we can define the width $\Delta\omega$ as

$$\Delta\omega \equiv \frac{\omega_0 \delta}{2}. \tag{36}$$

From the general theory of parametric resonance, the resonance wave number $k_{\rm r}$ is given by

$$k_{\rm r} = \frac{m}{2}. \tag{37}$$

It is convenient to convert $k_{\rm r}$ into the resonance frequency $f_{\rm r}$ of the waves as

$$f_{\rm r} = 1.2 \times 10^4\,\mathrm{Hz} \times \left(\frac{m}{10^{-10}\,\mathrm{eV}}\right). \tag{38}$$

This frequency corresponds to the VLF (very low frequency) band, 3–30 kHz. The existing FAST (Five-hundred-meter-Aperture Spherical radio Telescope) has a frequency band from 70 MHz to 3 GHz [27]. Hence, this detector can survey a mass range from 10^{-7} eV to 10^{-5} eV. The SKA (Square Kilometre Array) has frequency ranges of 50 MHz to 350 MHz (SKA-low) and 350 MHz to 14 GHz [28]. Now, this detector will survey a mass range from 10^{-7} eV to 10^{-4} eV. If we consider a heavier axion with mass $m \sim 1$ eV, the resonance frequency is that of visible light around 10^2 THz.

On halo scales of the Galaxy, the energy density of axion dark matter is about 0.3 GeV cm^{-3} [29]. Hence, the growth rate can be estimated as

$$\begin{aligned}\Gamma_{\max} &= \frac{1}{4}\lambda m \Phi_0 \\ &\simeq 5.4 \times 10^{-29}\,\mathrm{eV} \times \left(\frac{\lambda}{(10^{16}\,\mathrm{GeV})^{-1}}\right)\sqrt{\frac{\rho}{0.3\,\mathrm{GeV\,cm^{-3}}}}.\end{aligned} \tag{39}$$

Notice that this quantity is independent of the mass of the axion. In fact, the growth rate is determined by the coupling constant and the energy density of the axion dark matter. From this growth rate, we can estimate the time scale, $t_{\times 10}$, for the amplitude to become ten times greater, as

$$t_{\times 10} = 4.3 \times 10^{28}\,\mathrm{eV}^{-1} \times \left(\frac{(10^{16}\,\mathrm{GeV})^{-1}}{\lambda}\right)\sqrt{\frac{0.3\,\mathrm{GeV\,cm^{-3}}}{\rho}}. \tag{40}$$

Note that the time corresponding to 1 pc is given by $t_{1\,\mathrm{pc}} \simeq 1.6 \times 10^{23}\,\mathrm{eV}^{-1}$. Thus, if we fix the coupling constant to avoid too much enhancement of the amplitude after 10 Mpc propagation, the fraction of the axion must be constrained to be $\rho \leq 10^{-4} \times 0.3\,\mathrm{GeV\,cm}^{-3}$. Therefore, we can obtain a stringent constraint on the the fraction of axion dark matter in the universe.

The parametric resonance occurs in the frequency band

$$f_{\mathrm{r}} - \frac{\Delta f}{2} \lesssim f_{\mathrm{r}} \lesssim f_{\mathrm{r}} + \frac{\Delta f}{2}, \tag{41}$$

where Δf is given by

$$\Delta f = 2.6 \times 10^{-14}\,\mathrm{Hz} \times \left(\frac{\lambda}{(10^{16}\,\mathrm{GeV})^{-1}}\right)\sqrt{\frac{\rho}{0.3\,\mathrm{GeV\,cm}^{-3}}}. \tag{42}$$

Since the band is very narrow, the circularly polarized monochromatic wave grows sharply at the resonance frequency.

If the electromagnetic waves go through near the core of the Galaxy, the energy density of dark matter gets enhanced [29]:

$$\rho \lesssim 0.3 \times 10^{6}\,\mathrm{GeV\,cm}^{-3}. \tag{43}$$

In this situation, $t_{\times 10}$ becomes

$$t_{\times 10} = 4.3 \times 10^{25}\,\mathrm{eV}^{-1} \times \left(\frac{(10^{16}\,\mathrm{GeV})^{-1}}{\lambda}\right)\sqrt{\frac{0.3 \times 10^{6}\,\mathrm{GeV\,cm}^{-3}}{\rho}}. \tag{44}$$

From this estimation, the amplitude of waves going through the Galaxy core is further amplified by about 10^2. Of course, we should apply our analysis to the parameter region consistent with the perturbation theory. At the resonance frequency, when the amplitudes of waves are highly amplified, the electromagnetic wave should be fully polarized, namely, parity$(t) \simeq \pm 1$. However, different parts of electromagnetic waves enter the axion dark matter with different relative phases. If we would like to detect the circular polarization, the detector should have a time resolution smaller than

$$\Delta t \sim \frac{\pi}{m} \sim 10^{-5}\,\mathrm{s} \times \left(\frac{10^{-10}\,\mathrm{eV}}{m}\right). \tag{45}$$

In the case of SKA1, the time resolution is approximately $64\,\mu\mathrm{s}$ [28]. Hence, in the mass range $m \sim 10^{-10}$–10^{-14} eV, current detectors can detect the enhancement of amplitude but cannot detect the circular polarization.

If we detected the resonance signal, we would be able to argue that axion dark matter exists. If we do not detect the resonance signal, we would be able to give a constraint on the energy density or the coupling constant. Therefore, we can say that future very-long-wavelength radio wave observations of this effect can give rise to stronger constraints on the coupling constant and/or the density of axion dark matter.

5. *The speed of light* In axion electrodynamics, the dispersion relation in the axion background reads

$$\omega^2 = k^2 \left(1 + \epsilon_A \lambda \frac{m}{k} \Phi_0 \sin{(mt)}\right). \tag{46}$$

The phase velocity $v_{\rm p}$ is given by

$$v_{\rm p} \equiv \frac{\omega}{k} = \sqrt{1 + \epsilon_A \lambda \frac{m}{k} \Phi_0 \sin(mt)}. \tag{47}$$

Then, the deviation from the speed of light $\delta c_{\rm p}$ is given by

$$\begin{aligned} \delta c_{\rm p} &\equiv \left| v_{\rm p} - 1 \right| \\ &\leq \left| \sqrt{1 + \epsilon_A \lambda \frac{m}{k} \Phi_0} - 1 \right| \simeq \frac{\lambda \sqrt{\rho}}{\sqrt{2} k}. \end{aligned} \tag{48}$$

For example, if we observe visible light in the wavelength range 380–750 nm, we find the relative deviation of the speed of light:

$$\delta c_{\rm p} \simeq 4.3 \times 10^{-29} \times \left(\frac{\lambda}{(10^{16}\,{\rm GeV})^{-1}} \right) \left(\frac{l_{\rm em}}{500\,{\rm nm}} \right) \sqrt{\frac{\rho}{0.3\,{\rm GeV\,cm^{-3}}}}. \tag{49}$$

Here, $l_{\rm em}$ is the wavelength of the visible light.

In fact, the group velocity is more relevant to observations. The group velocity $v_{\rm g}$ is given by

$$v_{\rm g} \equiv \frac{\partial \omega}{\partial k} = \frac{1}{2\omega} \left(2k + \epsilon_A \lambda m \Phi_0 \sin\,(mt) \right). \tag{50}$$

The deviation from the speed of light $\delta c_{\rm g}$ is given by

$$\begin{aligned} \delta c_{\rm g} &\equiv \left| v_{\rm g} - 1 \right| \\ &\simeq \left| 1 + \frac{1}{8} \lambda^2 \frac{m^2}{k^2} \Phi_0^2 \sin^2\,(mt) - 1 \right| \lesssim \frac{\lambda^2 \rho}{4k^2}. \end{aligned} \tag{51}$$

Notice that the linear term is canceled out in the above formula[1] and the deviation of the group velocity is given by the square of that of the phase velocity,

$$\delta c_{\rm g} = \frac{1}{2} (\delta c_{\rm p})^2. \tag{52}$$

Thus, we can estimate $\delta c_{\rm g}$ as

$$\delta c_{\rm g} \simeq 9.4 \times 10^{-58} \times \left(\frac{\lambda}{(10^{16}\,{\rm GeV})^{-1}} \right)^2 \left(\frac{l_{\rm em}}{500\,{\rm nm}} \right)^2 \left(\frac{\rho}{0.3\,{\rm GeV\,cm^{-3}}} \right). \tag{53}$$

The relative deviation from the speed of light δc is constrained by observations of gamma-ray bursts [30] as

$$\delta c \lesssim 10^{-21}. \tag{54}$$

Since δc_g is much smaller than the current observational constraint, we can say that there is no constraint on the energy density of the axion field or the coupling constant from the speed of light.

[1] We thank Tomohiro Fujita for pointing out this fact.

6. *Conclusion* Since the axion is one of the candidates for dark matter, it is worth seeking a method for detecting axions. In this paper, we considered axions in the mass range 10^{-13} eV to 10^3 eV. We focused on two consequences of the coherent oscillation of axion dark matter and a coupling to the electromagnetic field through the Chern–Simons term. First, we studied the parametric resonance of the gauge field induced by the coherently oscillating axion. It turned out that, as a result of the resonance, the amplitude of electromagnetic waves is enhanced and circularly polarized monochromatic waves are generated. We found that future very-long-wavelength radio wave observations of this effect can give rise to stronger constraints on the coupling constant and/or the density of axion dark matter. Second, we studied the velocity of light in the background of axion dark matter. We found that the dispersion relation is modified and the speed of light shows oscillations in time, but this modification is too tiny to be observed.

In this letter, we have discussed modification of the dispersion relations which leads to the change of the speed of light. However, this effect was very small in axion electrodynamics. This would also happen to gravitational waves. We report the detailed analysis in a future work.

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