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Dilute axion stars converting to photons in the Milky Way's magnetic field

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Abstract: In this paper we examine the possibility of dilute axion stars converting to photons in the weak, large-scale magnetic field of the Milky Way and show that they can resonate with the surrounding plasma and produce a sizable signal. We consider two possibilities for the plasma: free electrons and HII regions. In the former case, we argue that the frequency of the photons will be too small to be observed even by space-based radio telescopes. In the latter case, their frequency is larger, safely above the solar wind cut-off. We provide an estimate of the flux as a function of the decay constant and show that for $f_a < 2 \times 10^{11}$ GeV, the signal will be above the radio emission of the solar system's planets and it could potentially be detected by the NCLE instrument which is on board the Chang'e-4 spacecraft. Finally, we calculate the time scale of decay of the axion star and demonstrate that back-reaction can be neglected for all physically interesting values of the decay constant, while the minimum time scale of decay is in the order of a few hours.

Keywords: Axions and ALPs, Particle Nature of Dark Matter

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Contents

1 Introduction

The axion, initially proposed as a solution to the strong CP problem [1, 2], is now one of the most well-motivated candidates of dark matter [3–5]. The axions are stable bosons, with large occupation numbers and can re-thermalize through their gravitational interactions forming a Bose-Einstein condensate (BEC) [6, 7]. Owing to the large occupation number of the ground state, the BEC condensate has been treated classically as a localised, coherently oscillating clump called an axion star, if the kinetic pressure is balanced by gravity and axiton or oscillon, if it is balanced by self-interactions. Generally, when an axion star is supported only by its self-interactions, such as the cosine potential, it is considered dense with radius $mR \sim 1$ [8] and also decays through scalar radiation on a time-scale of $10^3 m^{-1}$ [9, 10].

On the other hand, if both gravity and the leading term in the self-interactions are taken into account, the size is $mR \sim \frac{M_{pl}}{f_a}$, where $M_{pl} = \frac{1}{\sqrt{8\pi G}} = 2.4 \times 10^{18}\,\text{GeV}$ is the reduced Planck mass and f_a is the axion decay constant [10, 11]. Since the axion decay constant ranges from $10^9\,\text{GeV} < f_a < M_{pl}$ in the case where the Peccei-Quinn symmetry is broken during inflation and $10^9\,\text{GeV} < f_a < 10^{11}\,\text{GeV}$ in the classic axion window [12], these axion stars can be quite large for a wide range of decay constants. In contrast to dense axion stars, they are also long-lived, which makes them cosmologically very interesting [13]. However, it has been shown that dilute axion stars become increasingly unstable as f_a approaches M_{pl} [14], because their binding energy becomes large and relativistic contributions need to be taken into account. Therefore, we will limit our analysis in the range $10^9\,\text{GeV} < f_a < 10^{15}\,\text{GeV}$.

The axion can also interact with electromagnetic fields and several venues have been proposed for their detection [15]. Of particular interest is the Primakoff effect [16], which is the interaction of an axion with a magnetic field to produce a real photon.

The universe is abundant with magnetic fields and many astrophysical settings have been considered in the literature as possible "laboratories" where the axion to photon conversion could be detected. These range from pulsars [17–22] and magnetars [23–25], to white dwarfs [26–28], to AGN's [29, 30], to the galactic magnetic field [31–34].

In this paper, we will consider the possibility of an axion star converting to photons in the Milky Way's magnetic field. The strength of the magnetic field is of the order 1μG and its coherence length is of the order of the galactic scale [35]. We will confirm that the flux emitted from dense axion stars in this magnetic field is negligible [18]. However, there is the possibility of resonant conversion of axion stars to photons, if they find themselves in some region with cold plasma. By resonance, we mean that the axion mass equals the plasma frequency. It has been shown that in that case, the emitted power scales as $(mR)^6$, enhancing it significantly for dilute axion stars [36, 37]. The end result of the main calculation of this paper will be an expression for the emitted spectral flux density of *dilute* axion stars in some region with cold plasma.

When it comes to the plasma, the average electron density in the Milky Way is of the order of $n_e \sim 0.03\text{cm}^{-3}$, which implies a plasma frequency of the order $\omega_p = \sqrt{\frac{4\pi\alpha n_e}{m_e}} \sim 10^{-12}\text{eV}$ [38]. In the case of diffuse nebulae consisting of ionized hydrogen, the electron density ranges from 100-1000 cm^{-3}, with plasma frequencies in the 100-200 kHz range [39]. Because of energy conservation, the plasma frequencies that we estimated above will be the frequencies of the monochromatic photons that are emitted from the axion star. In the former case, those electromagnetic waves will be blocked by the solar wind, but in the latter case, they are in principal detectable by current space based radio telescopes, such as the NCLE [40].

Since the QCD axion's mass and decay constant must satisfy the equation $m_a f_a \approx (10^8\text{eV})^2$, due to the range of decay constant we are considering, our analysis does not cover the QCD axion, so we will only consider Axion-Like Particles (ALP's), for which the axion mass and the decay constant are independent [41].

In addition, we will demonstrate that our neglect of back-reaction effects is valid for $f_a > 10^7\,\text{GeV}$ and therefore for the entirety of the parameter space we are investigating. Finally, we will place a lower bound in the decay time scale, which will be in the order of a few hours.

To motivate our idea further, we can make an order of magnitude estimate of the axion star number in the Milky Way: let's assume that only 1% of the Milky Way's dark matter mass, $10^{12}M_\odot$,is distributed in axion stars. A dilute axion star has a mass of the order $10\frac{M_{pl}f_a}{m}$. For $m \sim 10^{-12}\text{eV}$ and $f_a \sim 10^{13}\,\text{GeV}$, a typical axion star mass is $10^{-4}M_\odot$. These should be distributed over the galactic halo, but since we are only interested in those in the galactic disk, their number is $10^{14}\frac{V_{disk}}{V_{halo}} \sim 10^{11}$, where we used a typical radius of the halo 30 kpc and a disk radius of 15 kpc and height of 300 pc [42]. This is indeed a huge number which makes the study of their resonant conversion in the Milky Way's magnetic field an intriguing possibility.

The paper is organised as follows: in section 2, we establish our formalism that describes a dilute axion star. In section 3, we review some properties of the Milky Way's magnetic field, its free electron and HII distribution and finally discuss some prospects of detection of the emitted radiation by radio telescopes. In section 4, we outline the derivation of the conversion of an axion star to photons in a constant magnetic field, in the presence of cold plasma, and apply it to the case of a dilute star, while we also give an estimate of the spectral flux density of photons that will arrive at Earth from such an event. In section 5 we estimate the decay time-scale of the axion star and we conclude in section 6 with some comments on future venues for research.

2 Dilute axions stars

In this paper we will mainly focus on dilute axion stars with gravitational as well as attractive self interactions. Also, we focus on ALP's for which the axion decay constant f_a and the axion mass m_a are independent from each other. The action for a scalar field ϕ which describes the axion star, coupled to a gravitational potential Φ with attractive $\lambda\phi^4$ interactions is [43]:

$$S = -\int d^4x\sqrt{-g}\left(\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial\nu\phi + \frac{1}{2}m^2\phi^2 - \frac{\lambda}{4!}\phi^4\right) \tag{2.1}$$

with metric:

$$ds^2 = -(1+2\Phi(\vec{x},t))dt^2 + d\vec{x}\cdot d\vec{x} \tag{2.2}$$

Throughout this paper we will assume that $\lambda = \mathcal{O}(1)\frac{m^2}{f_a^2}$ and we'll ignore the order 1 constant, since we are interested in order of magnitude estimates. In the non-relativistic limit:

$$\phi = \frac{1}{\sqrt{2m}}(\psi e^{-imt} + \psi^\star e^{imt}) \tag{2.3}$$

the equation of motion is the Gross-Pitaevskii equation:

$$i\partial_t\psi = -\frac{1}{2m}\nabla^2\psi + m\Phi\psi - \frac{\lambda}{8m^2}|\psi|^2\psi \tag{2.4}$$

while the potential satisfies the usual Poisson equation:

$$\nabla^2\Phi = 4\pi Gm|\psi|^2 \tag{2.5}$$

A stationary, spherically symmetric solution to the above equations is given by $\psi = e^{-i\mu t}\chi(r)$, where μ can be considered as the chemical potential. As a side remark that will be useful later on, we observe that if we insert this Ansatz into equation (2.3), we get:

$$\phi = \sqrt{\frac{2}{m}}\chi(r)\cos(\omega t) \tag{2.6}$$

where we have identified the frequency ω with $\omega = \mu + m$ [44]. Since we are interested in bound states, it holds that $0 < \frac{\omega}{m} < 1$. This matches the Ansatz of the scalar field ϕ that has been used by other authors to study non-relativistic axion stars [10, 36, 37], with the difference of the $\sqrt{\frac{2}{m}}$ factor in front.

To continue, we define the small parameter $\delta = \frac{4m^2}{\lambda M_{pl}^2}$. Notice that if we plug in the value of λ in terms of the axion mass and decay constant, we get $\delta = 4\frac{f_a^2}{M_{pl}^2}$, which is indeed small

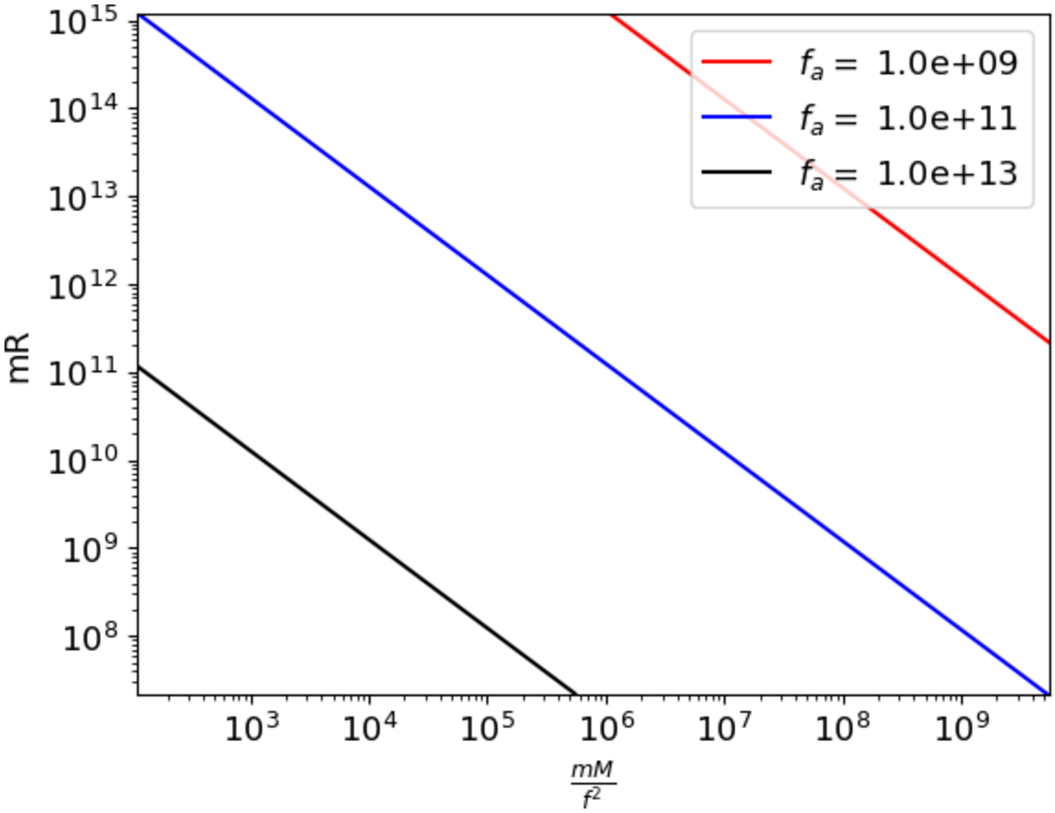

Figure 1. The mass-radius graph of dilute axion stars for three different values of f_a. Note that we have reverted back to the usual definitions of the dimensionless mass and radius that are found in the literature. The star becomes smaller as $f_a \to M_{pl}$.

for a wide range of physically relevant decay constants [12]. We rescale the wavefunction, the potential and the lengths to find the dimensionless forms of the above equations:

$$\chi(r) = \sqrt{\frac{m}{4\pi G}}\delta\tilde{\chi}(r), \quad \vec{x} = \frac{\vec{\tilde{x}}}{\sqrt{\delta}m}, \quad \Phi = \delta\tilde{\Phi} + \frac{\mu}{m} \tag{2.7}$$

The equations of motion become:

$$\tilde{\nabla}^2\tilde{\chi} = 2\left(\tilde{\Phi}\tilde{\chi} - \tilde{\chi^3}\right) \tag{2.8}$$

$$\tilde{\nabla}^2\tilde{\Phi} = \tilde{\chi^2} \tag{2.9}$$

They satisfy the boundary conditions $\tilde{\chi}'(0) = 0, \tilde{\chi}(\tilde{x} \to \infty) = 0, \tilde{\Phi}'(0) = 0$, while the condition $\Phi(\tilde{x} \to \infty) = 0$ implies that $\tilde{\Phi}(\tilde{x} \to \infty) = -\frac{\mu}{\delta m}$. We see from the last equation that $\frac{\mu}{m} \sim \delta \ll 1$ for the entire range of axion decay constants that we are considering. Therefore, in this non-relativistic limit, we will set $\mu = 0$ and $\omega = m$.

Equations (2.8) can be solved with the shooting method: for a given central amplitude of the scalar field $\tilde{\chi_0}$, we vary the central amplitude of the potential $\tilde{\Phi}_0$ until we find a solution that satisfies the boundary conditions [45]. Having found the solution, we can also compute the rescaled mass of the axion star $\tilde{M} = \frac{4\pi G m M}{\sqrt{\delta}}$:

$$\tilde{M} \approx \int d^3\tilde{x}\tilde{\chi}^2 \tag{2.10}$$

as well as the radius that contains 99% of its mass. The mass-radius graph generally contains two different branches, the dilute and the transition branch [10, 44–46]. We are only interested in the dilute branch whose mass-radius graph is depicted in figure 1 and we confirm that $M \sim \frac{1}{R}$. We have also verified that the dimensionless radius scales with the central amplitude as $mR \sim \frac{1}{\sqrt{\tilde{\chi}_0}}$

3 Properties of ISM and radio telescopes

Before tackling the question of the emitted flux of photons from the axion star, we will consider some properties of the ISM of the Milky Way, such as its large scale magnetic field and two different regions where a resonant conversion may take place, the free electrons and HII regions in nebulae.

3.1 Galactic magnetic field

The magnetic field of the galaxy that we are considering in this work has two components, a large scale one and a small scale one.

The large scale component is coherent on length scales of the order of the galaxy and its strength is typically around $1.5 - 2\mu G$. It reaches $6\mu G$ in the solar neighborhood and even $10\mu G$ towards the galactic center. Its structure also seems to follow the spiral arms [35]. For the purposes of this discussion, the important point is that it is coherent on scales much larger than the size of the axion star and we will consider a value of $1\mu G$ for its strength. We will say a few things about the small scale component towards the end, but we will ignore it for the remainder of this paper.

3.2 Free electron density

Regarding the free electron density in the Milky Way disk, that is of the order 0.03cm^{-3} [38]. Detailed models of the electron density in the Milky Way indicate that the electron density can be as high as $n_e = 0.2cm^{-3}$ in the thin disk, while the Local Arm has relatively low density with $n_e = 0.0057cm^{-3}$.

The plasma frequency is given by [38]

$$\omega_{pl} = 8.97\text{kHz} \left(\frac{n_e}{cm^{-3}}\right)^{1/2} \sim 6 \times 10^{-12}\text{eV} \left(\frac{n_e}{cm^{-3}}\right)^{1/2} \tag{3.1}$$

Given the range of values for the electron density quoted above, the range of plasma frequencies, and therefore axion masses, that we can probe are 0.6 KHz–4 kHz $\rightarrow 4 \times 10^{-13}\text{eV}$–$26.3 \times 10^{-13}\text{eV}$. Unfortunately, any electromagnetic waves coming from space with frequency below 30 MHz are blocked by the ionosphere. In addition to that, the solar wind at the Earth's radius can block frequencies that are below 30 kHz. Thus, we conclude that axion stars conversions in environments with free electrons will not produce a detectable flux.

3.3 HII regions

We turn to diffuse and planetary nebulae in the interstellar medium with HII regions, that is, ionized hydrogen and electrons. These are formed by stars with temperatures $T \sim 10^4 K$

that emit UV photons that can ionize the surrounding hydrogen gas, forming the well-known Strömgren radius [47]. The ionization fraction $x = \frac{n_e}{n}$, where n is the number density of protons and neutral hydrogen atoms, is equal to unity and the electron densities are generally in the range $100 - 1000\text{cm}^{-3}$ [39, 48]. From equation (3.1), these densities correspond to plasma frequencies $90 - 285\text{kHz} \Rightarrow 6 \times 10^{-11} - 2 \times 10^{-10}\text{eV}$. There are also ultracompact HII regions that can reach densities $n_e \geq 10^4\text{cm}^{-3}$ [49], which would correspond to plasma frequencies $\omega_{pl} \geq 897\text{kHz} = 5.9 \times 10^{-10}\text{eV}$. We see that the frequency of photons produced in HII regions will be safely above the solar wind's cut-off frequency at the Earth's location. We have ignored here the contribution of protons to the plasma frequency since their mass is much greater than the electron mass.

3.4 Radio telescopes

One way to observe the low frequencies we are considering here is with lunar or space based telescopes that will not face the issue of the ionosphere. So far, there have been four space or lunar based missions that probed frequencies below 10 MHz [50], with the most recent one being the Netherlands Chinese Low Frequency Explorer (NCLE) on board the Chang'e-4 satellite, which has landed on the far side of the Moon and is able to detect frequencies in the range 80 kHz–80 MHz [40]. Hence, it could potentially detect a radio signal from the conversion of an axion star to photons in a HII region. Several other proposals of radio telescopes in space are also described in [50] that aim to probe the frequency range that is relevant in this paper.

4 Spectral flux density

Having discussed the different environments where the conversion of an axion star to photons may take place, let us now turn to the calculation of the emitted flux of radio photons that will arrive to Earth when the conversion takes place in a HII region. We will derive an expression for the emitted power from a dilute axion star and demonstate that it can be much larger than the flux from a dense axion star, as well as the flux of the solar system's planets.

To begin, we briefly review the derivation of the emitted flux from an axion star in an external, constant magnetic field. The interaction of the axion with the electromagnetic field is given by the interaction Lagrangian:

$$\mathcal{L}_{\text{int}} = -\frac{g_{a\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} \tag{4.1}$$

We will make a few simplifying assumptions: firstly, we expand the electromagnetic fields and current in the small parameter $g_{a\gamma}\phi_0$:

$$\mathbf{E} = \mathbf{E}^{(0)} + \mathbf{E}^{(1)} + \ldots, \qquad \mathbf{B} = \mathbf{B}^{(0)} + \mathbf{B}^{(1)} + \ldots \tag{4.2a}$$

We also assume zero background electric field and consider the Ansatz of the axion field $\phi(r,t) = \phi_0\cos(\omega t)\text{sech}(r/R)$. This choice implies that we will not take back-reaction effects into account, something that we will justify in the next section. The interaction Lagrangian (4.1) implies the effective current and charge densities $\mathbf{J}_{\text{eff}} =$

$-g_{a\gamma}\sin(\omega t)\text{sech}(r/R)\mathbf{B}_0$ and $\rho_{\text{eff}} = -g_{a\gamma}\nabla\varphi \cdot \mathbf{B}_0$. Using the usual definition of electric and magnetic fields in terms of the potentials, we obtain the wave equations:

$$\left(-\nabla^2 + \frac{\partial^2}{\partial t^2}\right) A^0 = \rho_{\text{eff}} \tag{4.3a}$$

$$\left(-\nabla^2 + \frac{\partial^2}{\partial t^2}\right) \mathbf{A} = \mathbf{J}_{\text{eff}} \tag{4.3b}$$

where $\mathbf{A}$ and A^0 are first order in $g_{a\gamma}\phi_0$.

In Lorentz gauge, it is enough to solve equation (4.3b), since we can always solve for A^0 from the equation $\partial_t A^0 + \nabla \cdot \mathbf{A} = 0$.

The details of the solution are analyzed in [36, 37, 51] and we will only give the main result here for the emitted power per solid angle:

$$\frac{dP}{d\Omega} = \frac{\pi^4(g_{a\gamma}\varphi_0\omega^2R^2)^2}{32k\omega}\left(\frac{\tanh(\pi kR/2)}{\cosh(\pi kR/2)}\right)^2 |\mathbf{B}_0|^2 \tag{4.4}$$

where k is the wave-vector of the emitted photons and it is equal to $k = \omega\sqrt{1 - \frac{\omega_p^2}{\omega^2}}$, if we also include cold plasma. We have implicitly assumed that the gyrofrequency $\omega_B = \frac{\sqrt{4\pi\alpha}B_0}{m_e}$ is much smaller than the frequency of radiation ω, which is true for the values we are considering here: $\omega_B = 10^{-15}\text{eV} \ll \omega = 10^{-10}\text{eV}$. One final assumption is that the propagation of the photons is perpendicular to the galactic magnetic field, because we are mainly interested in an order of magnitude estimate of the effect.

We see that when the axion star is far from resonance, the power peaks for sizes $\omega R \sim 1$ while it is exponentially suppressed if $\omega R \gg 1$. We are interested in studying the power emitted when the star is in resonance, so we take $\omega \to \omega_p \sim 10^{-10}\text{eV}$. The power becomes:

$$\frac{dP}{d\Omega}(\omega \to \omega_p) \approx \frac{(g_{a\gamma}\phi_0)^2}{128}\frac{(\pi\omega R)^6}{\omega^2}\left(1 - \frac{\omega_p^2}{\omega^2}\right)^{1/2}|\mathbf{B}_0|^2 \tag{4.5}$$

In the spirit of the order of magnitude estimate that we are attempting, let us assume that this conversion takes place 1 kpc away from Earth, which is a typical galactic distance. We define the spectral flux density of the incoming radiation as $S = \frac{1}{r^2\mathcal{B}}\frac{dP}{d\Omega}$ where $\mathcal{B}$ is the Doppler shift of the central frequency and we estimate it as $\mathcal{B} \sim \frac{0.1\omega}{2\pi}$. For a dense axion star, the value of the spectral flux density is of the order: $S \sim 10^{-21}Jy$, which is indeed negligible.

However, the $(\omega R)^6$ term is promising: dilute axion stars with $\omega R \gg 1$ can significantly enhance the flux that arrives at Earth. To find the power emitted from a dilute axion star in resonance, we make the substitution $\phi_0 \to \sqrt{\frac{1}{2\pi G}}\delta$, which comes from combining equations (2.7) and (2.6). Assuming that $g_{a\gamma} \sim \frac{\alpha}{f_a}$ and with the approximation $\omega \approx m$, our estimate is:

$$S \sim 10^{-21}\text{Jy}\frac{1}{\delta^2}\left(\frac{1kpc}{r}\right)^2\left(\frac{10^{-10}\text{eV}}{m}\right)^3\left(\frac{B_0}{1\mu G}\right)^2 \tag{4.6}$$

where we have also approximated $mR \sim \frac{1}{\sqrt{\delta}}$. We see that since $\delta \ll 1$ for a wide range of decay constants, this flux can be quite huge.

We would like to compare this flux density with the fluxes that come from the planets of our solar system. In the frequency range 100-300 kHz, the largest flux comes from Saturn which reaches approximately $10^{-19}\frac{\mathrm{W}}{\mathrm{Hz\,m^2}} = 10^7$Jy [52]. Setting the electron density to 400cm^{-3}, we find that $S > 10^7$Jy for $f_a < 2 \times 10^{11}$ GeV.

5 Decay time scales

We estimate in this section the time that it will take for the axion star to convert all its mass to photons. The mass of a dilute axion star is of the order of $M \sim 10\frac{f_a M_{pl}}{m}$ [10]. We assume the star is in resonance with the surrounding plasma. The timescale over which the star will lose the entirety of this mass is roughly given by:

$$T = \frac{M}{P} \sim 10^4 \frac{M_{pl}^2 m \delta^{5/2}}{B_0^2} \tag{5.1}$$

where we have estimated the emitted power to be $P \sim 10^{-3}\frac{1}{\delta^2}\frac{B_0^2}{m^2}$. We are ignoring back-reaction effects here, so in order for this estimation to make sense, we need $T > \frac{2\pi}{m}$, the decay time scale needs to be longer than the period of the radiation [37].Solving for the small parameter δ, we find

$$\delta > \left(\frac{10^{-2}B_0}{mM_{pl}}\right)^{4/5} \Rightarrow f_a > M_{pl}\left(\frac{10^{-2}B_0}{mM_{pl}}\right)^{2/5} \tag{5.2}$$

For $B_0 = 1\mu$G and $m = 10^{-10}$eV, this gives the lower bound $f_a \gtrapprox 10^7$ GeV. This tells us that for most of the parameter space, back-reaction can indeed be ignored. For $f_a = 10^9$ GeV, the lower bound on the decay timescale is $T \sim 3$hr.

6 Conclusions and outlook

We have considered the possibility of axion stars converting to photons in the magnetic field of the Milky Way. The high number of axion stars in the galactic disk that we estimated in the Introduction make this a possibility worth considering. We showed that the weak magnetic field of the galaxy is not enough to efficiently convert a dense axion star to photons in vacuum. However, if an axion star is in a plasma and its frequency is close to the plasma frequency, the dependence of the emitted flux on $(mR)^6$ implies that a dilute axion star will produce a sizable flux.

Beginning from this observation, we considered two different possibilities of a plasma in the Milky Way, the free electrons and the diffuse nebulae with HII regions. In the former case, we argued that the photons produced will have frequencies far below the solar wind cut-off and we will never be able to observe them with lunar based radio-telescopes. In the latter case, however, the electron density is 10^4 time larger, leading to photons with frequencies $\nu \geq 100$kHz safely above the solar wind threshold and within the target range of current lunar based telescopes, such as NCLE.

Our main calculation involved the estimation of the spectral flux density that will arrive at Earth if a dilute axion star resonated with its surrounding plasma and converted its mass to photons. We showed that for axion decay constants $f_a < 2 \times 10^{11}$ GeV the flux is larger than the radio flux emitted from Saturn, which is the dominant one from the solar system's planets in this frequency range.

Finally, we estimated the time scale over which the star will radiate. We demonstrated that back-reaction effects can be ignored for the entirety of the parameter space that we consider in this work and found that an axion star will need at least a few hours to lose all its mass. However, it is an open question whether the star will transition to different configurations as it decays, so that it eventually moves out of resonance. Ref. [53] did this analysis for dense axion stars supported by their self-interactions and found that the axion stars grow in size, their frequency increases and they go out of resonance after a certain time-scale. It is not clear whether the same thing can happen with dilute stars because, to a very good approximation, $\omega \sim m$. An analysis in the vein of [54] could shed some light on this question.

A coulpe of more comments are in order regarding this proposal. Firstly, we have ignored the small scale component of the galactic field that is related to the turbulent Interstellar Medium . This component has a shorter correlation length than the large-scale component we used in this study and its strength is $5.5\mu G$ [35]. It has been shown that it can enhance the conversion of diffuse axions to photons by many orders of magnitude and it should be taken into account in future work [31, 33].

Also, we have not considered the distribution of axion stars in the galactic plane, which, to our knowledge, is not known. This makes it difficult to estimate the number of conversions that we could potentially observe. A more detailed study should take the axion star distribution into account, combined with the disribution of HII in the Milky Way, as shown in [55]. This should provide us with an accurate estimation of the frequency of these events.

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