Fast radio bursts from axion stars moving through pulsar magnetospheres

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We study the radio signals generated when an axion star enters into the magnetosphere of a neutron star. As the axion star moves through the resonant region where the plasma-induced photon mass becomes equal to the axion mass, the axions can efficiently convert into photons, giving rise to an intense, transient radio signal. The energy released is determined by the axion star mass and conversion probability. Similarly, the peak frequency of the emitted radio signal is fixed by the axion mass, while cosmological redshift and Doppler shift could give rise to a wide range of frequencies. In particular, we show that a dense axion star with a mass $\sim 10^{-13} M_\odot$ composed of $\sim 10 \mu$eV axions can account for most of the mysterious fast radio bursts in a wide frequency range.

I. INTRODUCTION

Weakly coupled pseudoscalar particles such as axions, that arise from a solution to the strong CP-problem [1–7], or more generic axion-like particles (ALPs) predicted by string theory [8–10], are promising dark matter (DM) candidates and may contribute significantly to the energy density of the Universe [11–13]. In recent years, renewed increased interest in axion DM has motivated a broad experimental program (see e.g. Ref. [14] for a recent review). Most of these experimental searches are based on the Primakoff process [15], whereby axions transform into photons in external magnetic fields and vice versa.

Low mass (long wavelength) axions or ALPs that contribute appreciably to the DM must have extremely high occupation numbers, and can be modeled by a classical field condensate. If such condensates or other substructures survive to the present, the large number density in astrophysical environments makes it possible to probe their existence indirectly through the detection of low energy photons; for axion masses consistent with the observed DM density, $m_a \sim$ a few $\mu$eV, the emitted photons have frequencies in the range probed by radio telescopes. Along these lines, signals resulting from the axion decay to two photons [16–17], or from resonant axion-photon conversion [18–20] have been recently explored.

If the Peccei-Quinn (PQ) symmetry [1] is broken after inflation, the axionic DM distribution is expected to be highly inhomogeneous, leading to the formation of axion miniclusters as soon as the Universe enters the matter-domination regime [21–23], which in turn may lead to the formation of dense boson stars [24, 25]. Boson stars made of axionic Bose-Einstein condensate are called axion stars, when the kinetic pressure is balanced by self-gravity, or axitons, when stabilized by self-interactions (see Ref. [26] for a recent review). In this scenario, part of the DM could be in the form of axion stars [27]. Gravitational microlensing could potentially constrain the fraction of DM in collapsed structures [28], but typical axion star signals fall in the femtolensing regime which is not robustly constrained [29]. Although their presence may be unveiled in future by observations of highly magnified stars [30], it is important to look for other experimental probes.

Such dense clumps of axion DM can lead to enhanced radio signals, which might explain the mysterious observation of Fast Radio Bursts (FRBs) [31, 32]. For instance, the oscillating axion configuration associated with a dilute axion star hitting the atmosphere of a neutron star was conjectured to induce dipolar radiation of the dense electrons in the atmosphere, which would in turn give rise to a powerful radio signal similar to the FRBs. A related proposal considered neutrons in the interior of the neutron star as the source of FRBs [33]. However, as pointed out in Ref. [34], the radius of a dilute axion star is about several hundred kilometers, which means that tidal effects will destroy it well before it can reach the surface of the neutron star, at about $10^6$ km. Moreover, the photon radiated at the surface of the neutron star has a plasma mass, which is much larger than the intrinsic frequency of the dipole radiation (equivalent to the axion mass). Hence, medium effects would greatly suppress the signal.

Even in the optimistic scenario of a dense axion star directly hitting the surface of a neutron star, this would lead to, at most, a $\mu$Jy radio signal [36], whereas FRBs range from $\mathcal{O}(0.1)$ to $\mathcal{O}(100)$ Jy (where 1 Jy=$10^{-23}$ erg $\cdot$ s$^{-1}$ $\cdot$ cm$^{-2}$ $\cdot$ Hz$^{-1}$). Their large dispersion measure suggests that the FRBs are of extragalactic origin, generated at redshift $0.1 \lesssim z \lesssim 2.2$. This means that the total energy released in an FRB is about $\mathcal{O}(10^{38})$ to $\mathcal{O}(10^{40})$ erg, and their observed millisecond duration requires that the radiated power reaches $10^{41}$–$10^{43}$ erg $\cdot$ s$^{-1}$. Although their origin and physical nature are still obscure [37–40], the fact that the energy released by FRBs is about a few percent of $10^{-14} M_\odot$ (where $1 M_\odot = 1.1 \times 10^{37}$ GeV is the solar mass), which is the typical axion star mass, and that their frequency...
(several hundred MHz to several GHz) coincides with
that expected from μeV axion particles, motivates us to
further explore whether the axion-FRB connection can
be made viable in a neutron star environment and tested
with the future data.]\\

In this letter, we propose a new explanation for FRBs
based on the resonant axion-to-photon conversion that
takes place when a dense axion star passes through the
resonant region in the magnetosphere of a neutron star,
as shown in Fig. 1. We will mainly focus on non-repeating
FRBs in this work, since repeating FRBs may correspond
to a different source class. So far, more than 60 non-
repeating FRBs have been observed mainly by Parkes, ASKAP, and UTMOST radio telescopes. Our ex-
planation of the non-repeating FRB signals roughly from
800 MHz to 1.4 GHz involves dense stars made of axions
with mass of about 10 µeV. By the Primakoff process,
the huge number of axions in the dense axion star can be
converted to radio signals within the strong magnetic
field through resonant effect in the resonant conversion
region of the magnetosphere of a pulsar. In the magneto-
sphere, the photon obtains a position-dependent effective
region of the magnetosphere of a pulsar. In the magneto-

II. AXION STAR – PULSAR ENCOUNTER

The properties of an axion star depend on its mass
M_a, and on the axion parameters, namely, mass m_a and
decay constant f_a. Dilute axion stars, supported by self-
gravity, have a radius

\[ R_a^{\text{dilute}} \sim \frac{1}{G_N M_a m_a^2} \approx 270 \left( \frac{10 \, \mu\text{eV}}{m_a} \right)^2 \left( \frac{10^{-12} M_\odot}{M_a} \right) \text{ km}, \]

where \( G_N \) is Newton’s constant of gravitation. Hence,
the typical radius of a dilute axion star is about sev-
eral hundred kilometers for stars in the mass range
\( M_a \sim 10^{-14} - 10^{-12} M_\odot \). The existence of a dense star
branch was first proposed in Ref. 47, where solutions
supported by self-interactions were described using non-
relativistic field theory. Nevertheless, it was pointed out
in Ref. 48 that such stars reach \( \gtrsim \mathcal{O}(1) \) field values
in the core. The axions are then relativistic and the
analysis in Ref. 47 is inconsistent (see also Refs. 49–
51). Since gravity is negligible inside such dense stars,
their profiles can instead be found as solutions of a Sine-
Gordon type equation. One is thus led to the natural
identification of stars in the dense branch with oscillons.
In contrast to the natural expectation that localized, fi-
nite energy configurations of the axion field decay within
\( \tau \sim 1/m_a \sim 6 \times 10^{-13} (10 \, \mu\text{eV}/m_a) \) s, oscillons can last \( \mathcal{O} \) (100-1000) oscillations, before disappearing into
a burst of relativistic axions. For a QCD axion in the
mass range of interest here, these timescales still fall short
of being of cosmological relevance. Nevertheless, flatter
potentials at large field values in well motivated ALP
models have been shown to feature much longer-lived osc-
illons, \( \tau > (10^8-9)/m_a \), and for plateau-like potentials
only lower bounds on their lifetime are known. Stable
dense profiles are also possible when \( f_a \gtrsim 0.1 M_\text{Pl} \). On
the other hand, axion stars could have been created
much after matter domination. Both the shape of the
potential and the initial field amplitude of the axion at
the start of the oscillations can trigger parametric am-
plification of axion fluctuations even if the PQ symmetry
is broken before inflation. Given that oscillons are attractor solutions, it cannot be excluded that dense
axion configurations are being generated and are present
in astrophysical settings such as pulsars. We will as-
sume their existence in the following discussion. In this
work, we assume that dense axion stars with a mass around
10^{-13} M_\odot can survive to the present, and have a chance to encounter a neutron star. If heavier stars are
stable, these would give a stronger signal.

For dense axion stars, the radius can be approximated
as

\[ R_a^{\text{dense}} \sim 0.47 \sqrt{g_{a\gamma \gamma} \times 10^{13} \text{ GeV}} \times \frac{10 \, \mu\text{eV}}{m_a} \left( \frac{M_a}{10^{-13} M_\odot} \right)^{0.3} \text{ m}, \]

with \( g_{a\gamma \gamma} \) being the axion-photon coupling, roughly of
order meter or even smaller, which makes it easy to avoid
tidal disruption.

It is worth noticing that tidal effects become important
when the distance of the axion star to the center of the
neutron star approaches the so called Roche limit:

\[ r_1 = R_a \left( \frac{2 M_\text{NS}}{M_a} \right)^{1/3}, \]

where \( M_{\text{NS}} \) is the neutron star mass (typically in the
range of 1.4 M_\odot–3 M_\odot). A gravitationally bound object
approaching a star closer than this radius will be dis-
rupted by tidal effects. For a 100 km dilute axion star,
the Roche limit is about 10^6 km, so it will be de-
stroyed long before it gets to the magnetosphere and the
resonant conversion region of the neutron star (which is
only about a thousand km from the neutron star). Tidal
disruption may quickly rip apart the dilute axion star,
producing a stream of axion debris that would then be

\[ 1 \text{ See Refs. } 31, 42 \text{ for alternative proposals not involving neutron stars.} \]
FIG. 1. Schematic diagram of the proposed FRB signal from dense axion stars. When a dense axion star passes through the resonant conversion region in the magnetosphere of a neutron star (where the effective photon mass equals the axion mass), powerful transient radio signals can be produced in the strong external magnetic field through the Primakoff process.

swallowed by the neutron star. It is conceivable that this subsequent interaction of the tidal debris with the neutron star leads to a multiplicity of radio signals, similar to repeating FRBs (mostly observed by CHIME), and this possibility deserves further investigation.

For a dense axion star, however, the radius is smaller than a meter and the Roche limit is below 10 km. Thus, a dense axion star can reach the resonant conversion region without being tidally ripped. Tidal forces will certainly stretch the axion star in the radial direction and compress it in the transverse direction. Since the resonant conversion region is located over a hundred Schwarzschild radii from the neutron star, we can use Newtonian gravity to estimate the tidal deformation ratio:

$$ \frac{\delta R_a}{R_a} = \frac{9M_{NS}}{8\pi \rho_{AS} r^3} $$

where $\rho_{AS}$ is the axion star density and $r$ is its distance from the neutron star. For typical values, the tidal deformation effect is negligible for a dense axion star. For example, when a $10^{-13}M_\odot$ dense axion star approaches a $1.5M_\odot$ neutron star at a distance of 100 km, $\delta R_a/R_a \sim 10^{-3}$.

The axion mass should lie around the observed FRB frequency, roughly from several $\mu$eV to several tens of $\mu$eV. Non-repeating FRBs can be produced when an axion star enters the resonant conversion region of the neutron star magnetosphere, and overlaps with this region for about several milliseconds on its inspiral fall onto the neutron star. The trajectory is schematically shown in Fig. 1. By radiating the radio signal, the axion star loses energy and shrinks to smaller radii. As we argue below, between 0.1% to 100% of the axion star energy can be released in the form of FRBs lasting several milliseconds.

III. FRBS FROM RESONANT AXION TO PHOTON CONVERSION

When a dense axion star enters the magnetosphere, it can produce radio signals from axion conversion into photons. We begin our discussion with the axion-photon interaction term

$$ \mathcal{L} = -\frac{g_{a\gamma\gamma}}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}, $$

where $a$ represents the axion field, $F_{\mu\nu}$ is the electromagnetic field strength, and $\tilde{F}^{\mu\nu}$ its dual. Several observations constrain the coupling $g_{a\gamma\gamma}$ to be below $g_{a\gamma\gamma} \leq 10^{-13}$ GeV$^{-1}$ for axion masses in the range between about 4 $\mu$eV and 16 $\mu$eV [61, 62]. This interaction allows the conversion of an axion to a photon in an external magnetic field and vice versa. Neutron star magnetospheres, featuring the strongest magnetic fields known in the Universe, are one of the best candidates to display this process. Due to the extremely small coupling $g_{a\gamma\gamma}$, however, the conversion probability is expected to be very small even in the magnetosphere of neutron star. On the other hand, the conversion rate can be significantly enhanced in the resonant conversion region of the magnetosphere, where the plasma mass equals the axion mass, as shown in Fig. 1. Indeed, the photon acquires a
mass due to the plasma effects in the magnetosphere (see e.g. [63] for a textbook discussion):

\[ m_\gamma(r) = \omega_p = \sqrt{\frac{\alpha n_e}{m_e}} = \sqrt{\frac{n_e}{7.3 \times 10^6 \text{ cm}^{-3}}} \mu\text{eV}, \quad (5) \]

where \( n_e(r) \) is the local electron density at a distance \( r \) from the center of the neutron star. For simplicity, we have used the Goldreich-Julian distribution [64]:

\[ n_e(r) = 7 \times 10^{-2} \frac{1 \text{ s}}{B(r) P} \frac{1 \text{ G}}{\text{ cm}^{-3}}, \quad (6) \]

where \( P \) is the rotation period of the neutron star (from milliseconds to several tens of seconds). As for the magnetic field \( B(r) \), we use the dipole approximation as the leading order approximation:

\[ B(r) = B_0 \left( \frac{r_{\text{NS}}}{r_c} \right)^3, \quad (7) \]

with \( B_0 \) being the magnetic field strength at the surface of the neutron star \( (r = r_{\text{NS}}) \), which can reach \( 10^{15} \text{ G} \) for a magnetar [65]. The typical scale for the magnetosphere or the Alfvén radius is of order 100 \( r_{\text{NS}} \sim 1000 \text{ km} \).

In the resonant conversion region, the photon effectively has almost the same mass as the axion due to plasma effects:

\[ \omega^2 = k_p^2 + m_a^2 \approx m_a^2(r_c), \quad (8) \]

where \( \omega \) is the axion-photon oscillation frequency. The mass degeneracy leads to maximal mixing and greatly enhances the conversion probability. The critical radius \( r_c \) for the resonant conversion region is obtained by enforcing the maximal mixing condition Eq. [8]:

\[ \left( \frac{r_{\text{NS}}}{r_c} \right)^3 \sim \left( \frac{m_a}{\mu\text{eV}} \right)^2 \left( \frac{10^{10} \text{ G}}{P} \right) \left( \frac{B_0}{1 \text{ G}} \right) \cdot (9) \]

At this distance, an infalling axion star will be moving with typical speed \( v_c = \sqrt{2G_NM_{\text{NS}}/r_c} \sim 0.2 \) if \( r_c \sim 10r_{\text{NS}} \).

When the dense axion star approaches the distance \( r_c \), resonant axion to photon conversion can occur. The conversion probability can reach \( \sim 0.1 \), if the conversion proceeds adiabatically. However, for most neutron stars the conversion develops in the non-adiabatic resonant regime [19], and we work under this assumption. The conversion rate is still much larger than in the non-resonant case, and it can be obtained from the well-known Landau-Zener probability:

\[ P_{a \rightarrow \gamma} = 1 - e^{-2\pi\beta}. \quad (10) \]

The non-adiabatic limit corresponds to small \( \beta \), and we have \( P_{a \rightarrow \gamma} \approx 2\pi\beta \) with

\[ \beta = \left. \frac{(g_{a\gamma\gamma} \omega_B)^2 / 2k_p}{d\omega_p/dr} \right|_{r=r_c}. \quad (11) \]

Here, \( k \equiv \sqrt{\omega^2 - (m_a^2 + \omega_p^2)/2} \) is the axion momentum in the diagonalized basis of the mixing equations. Taking the dipole configuration for the magnetic field and the Goldreich-Julian electron density distribution in the magnetosphere of the neutron star, we can derive

\[ \frac{d\omega_p}{dr} \bigg|_{r=r_c} = \frac{3\omega_p^2}{r} \bigg|_{r=r_c}. \quad (12) \]

We note that for typical parameters, close to the neutron star surface \( r \sim r_c \), the effective photon mass is larger than the axion mass. In this case, the emission of a photon is kinematically suppressed, impacting the viability of the mechanisms proposed in Refs. [33, 36].

As a dense axion star moves through the resonant region, the conversion power is \( W = \frac{P_{a \rightarrow \gamma} \text{d}M_a}{\text{d}t} \) with \( \text{d}M_a/\text{d}t \sim \pi R_c^2 \rho_A v_c \) and \( \rho_A = M_a/(4\pi R_c^3/3) \). Thus, we obtain the power:

\[ W \sim \left( \frac{M_a}{10^{-13} M_\odot} \right) \left( 10^7 \times P_{a \rightarrow \gamma} \right) \left( 10^{44} \text{ GeV} \cdot \text{s}^{-1} \right). \quad (13) \]

For the benchmark values \( B_0 = 10^{14} \text{ G}, m_a = 10 \mu\text{eV}, g_{a\gamma\gamma} = 10^{-13} \text{ GeV}^{-1}, \) conversion in a typical \( 1.4M_\odot \) pulsar rotating with \( P = 0.1 \text{ s} \) occurs with \( P_{a \rightarrow \gamma} \sim 2 \times 10^{-5} \) in the resonant region. Hence, to explain the typical output associated to FRBs, \( W \sim 10^{44} \text{ GeV} \cdot \text{s}^{-1} \), it seems natural to use a \( 10^{-13} M_\odot \) dense axion star.

The trajectory of the dense axion star is schematically shown in Fig. 1. Once the dense axion star enters the resonant region, it moves in the resonant region with gradually decreasing radius until it leaves the resonant region or it evaporates. The star moves about 10 km (several milliseconds) in the resonant region to produce enough energy to account for the FRBs.

The density flux of the radio signal can be obtained as:

\[ S = \frac{W}{4\pi d^2 \Delta B}, \quad (14) \]

where \( d \) is the source distance from the Earth and \( \Delta B \) is the bandwidth of the signal. To compare with current data [14, 45], we rewrite this as:

\[ \frac{E_{\text{FRB}}}{J} = \frac{F_{\text{obs}} \Delta B}{\text{Hz} \cdot \text{ms}} \left( \frac{d}{	ext{m}} \right)^2 \times 10^{-29} (1 + z), \quad (15) \]

where \( E_{\text{FRB}} \) is the energy released in a FRB (in Joules), \( d \) is the distance from the source to the radio telescope (in meters), and \( z \) is the redshift. For non-repeating FRBs, the released energy ranges from \( 10^{30} \) to \( 10^{33} \) J. The distance \( d \) varies from several hundred Mpc to several Gpc. Since the spectral information of the FRBs is largely unknown, the bandwidth \( \Delta B \) is chosen as the bandwidth of the radio telescope in current experiments [14, 45], i.e. the range of frequencies the telescope can measure. The fluence \( F_{\text{obs}} \) is the density flux \( S \) integrated over time.

For the benchmark values \( m_a = 10 \mu\text{eV}, M_a = 10^{-13} M_\odot, g_{a\gamma\gamma} = 10^{-13} \text{ GeV}^{-1} \) we can naturally explain
most of the observed $\mathcal{O}(0.1–100)$ Jy FRBs as shown in Fig. 2. The orange line in Fig. 2 depicts the upper limit for $M_a = 10^{-13} M_\odot$ with the same bandwidth $\Delta B \sim 340$ MHz, and the events below this line can be accounted for. The dashed orange line represents the upper limit for $M_a = 10^{-12} M_\odot$ and the same bandwidth, while we used $M_a = 10^{-13} M_\odot$ and $\Delta B \sim 31$ MHz for the magenta line. The red circles, black triangles, green diamonds and orange stars represent the 27 non-repeating FRBs observed by Parkes, 28 non-repeating events from ASKAP, 1 non-repeating event from Arecibo and 9 non-repeating events from UTMOST, respectively.

An FRB emitted with a frequency $\nu_0 = m_a/2\pi = 2.42$ GHz ($m_a/10 \mu eV$) in the axion rest frame will be observed at a lower frequency by the time it reaches a radio telescope on Earth due to the effects of gravitational and cosmological redshift:

$$\nu = \frac{\nu_0}{1 + z} \sqrt{1 - \frac{2G N M_{NS}}{r_c}}. \quad (16)$$

Using the appropriate cosmological and gravitational redshifts, the observed frequency ranges from 0.6 to 2.2 GHz for a 10 $\mu eV$ axion, as shown in Fig. 3. The variation of signal strengths and duration depends on the exact field geometry in the conversion region. The duration of the signal also depends on the motion of the neutron star through the resonant conversion region and on the redshift. On the other hand, for fixed axion mass, a larger pulsar rotational period $P$ means a smaller $r_c$, and hence a larger $B$, which leads to a larger conversion probability. Also a stronger magnetic field on the surface of the neutron star gives more intense signals.

We stress that this paper is aimed at explaining the broad features of FRBs, but there are a number of complicated astrophysical effects that are likely important in describing the detailed emission mechanisms for radiation from these events. Details of the geometry of the magnetosphere (e.g., the position of gaps and the neutral sheet) have a significant impact on the observed signals. Moreover, there are likely to be significant feedback effects in the conversion region. As the axion star moves through the field and plasma comprising the magnetosphere, it may exert radiation pressure on the surrounding plasma, exceeding the relatively small Thomson pressure due to the complicated plasma effects. We might expect the FRBs to be accompanied by broad-band signals from synchrotron radiation, curvature radiation and even inverse Compton radiation from accelerated particles. However,
the most sensitive instruments to the resulting spectral energy distribution are still radio telescopes.

IV. FUTURE DETECTION AND EVENT RATES

The smallest flux density that can be detected by a radio telescope can be written as:

$$S_{\text{min}} \approx 0.09 \text{ Jy} \left( \frac{1 \text{ MHz}}{\Delta B} \right)^{1/2} \left( \frac{1 \text{ ms}}{t_{\text{obs}}} \right)^{1/2} \left( \frac{10^3 \text{m}^2/\text{K}}{A_{\text{eff}}/T_{\text{sys}}} \right)$$

where $t_{\text{obs}}$ is the observation time. For the SKA Phase I [66], the effective area to system temperature ratio $A_{\text{eff}}/T_{\text{sys}} = 2.7 \times 10^3 \text{m}^2/\text{K}$. SKA can then detect a radio signal if $S > S_{\text{min}}$, within the frequency range from 0.45 to 13 GHz. For example, for $\Delta B = 100 \text{ MeV}$, $t_{\text{obs}} = 100 \text{ ms}$, $S_{\text{min}} = 3 \times 10^{-4} \text{ Jy}$. The sensitivity is expected to increase by more than an order of magnitude in Phase 2 of SKA, which will enhance its ability to detect even weaker FRBs by several orders of magnitude.

The event rate in our galaxy can be estimated as

$$N_{\text{year}} = \sigma v_0 n_{\text{AS}} n_{\text{NS}} f_{\text{NS}} V_{\text{galaxy}}$$

(17)

with $\sigma = \pi b^2 = \pi v_c^2/v_0^2(1 - 2G_N M_{\text{NS}}/r_c)^{-1}$ is the scattering cross section for the axion star with a virial velocity $v_0$ approaching the neutron star at an impact parameter $b$. There are about $10^9$ neutron stars in our galaxy. The number of axion stars is given by $n_{\text{AS}} = \kappa_{\text{AS}}/\rho_{\text{DM}} \approx \kappa_{\text{AS}} \times 10^{11} \text{ pc}^{-3}$, with the typical galactic DM density $\rho_{\text{DM}} = 0.3 \text{ GeV} \cdot \text{cm}^{-3}$, while $\kappa_{\text{AS}}$ is the fraction of the total DM density in axion stars. Finally, $f_{\text{NS}}$ represents the ratio of neutron stars with magnetic fields larger than $10^{13} \text{ G}$ on their surface. We thus have $N_{\text{year}} = \kappa_{\text{AS}} 10^{-2} f_{\text{NS}}$ in our galaxy. For the whole universe, the event rate per day is $10^{13} \kappa_{\text{AS}} f_{\text{NS}}/365 \sim 1000$, if we take $\kappa_{\text{AS}} = 10^{-2}$ and $f_{\text{NS}} = 10^{-5}$. Hence, we expect about one thousand events per day. This scenario satisfies the condition that the events should be sufficiently rare to ensure that the Galactic plane does not dominate the spatial distribution of observed events [67]. In future, the SKA can detect more and more FRB events and provide us with more detailed and accurate information to test our proposed axion-star explanation.

V. CONCLUSION AND OUTLOOK

We have proposed a new explanation for the origin of FRBs, based on the axion to photon conversion that ensues when a dense axion star moves through the resonant region in the magnetosphere of a pulsar. If there are more than one type of axions with different masses, there would also have been other FRBs with very different frequency range. At this time, we can only speculate whether feedback processes on the plasma surrounding the conversion region might give rise to broader band emission, explaining a larger fraction of the observations. The observed FRB energy output is naturally obtained for axion stars with masses around $10^{-13} M_{\odot}$ if the axion-photon conversion proceeds through the resonant, non-adiabatic regime. Most of the observed frequencies for non-repeating FRBs can be accommodated with a $10 \mu\text{eV}$ axion mass.

In this paper, we have not attempted to study the detailed dynamics for the capture of axion stars and decay of the orbits. We also leave a detailed study of the radio signals that can be generated when the debris of a dilute axion star enters into the magnetosphere of a neutron star for future work. In fact, tidally disrupted dilute axion stars may be responsible for the repeating FRBs. One possible mechanism is that different parts of the axion star debris fall in and cross the resonant conversion region at different times behaving as repeating FRBs. In addition, different sections of the axion debris could have different eccentricities, giving rise to different periods for crossing the resonant region. Our study can be extended to collisions of axion stars with other magnetized astrophysical sources.

In the future, the unprecedented sensitivity of SKA and other forthcoming radio telescopes may enable the spectral properties of FRBs to be unraveled. The many observed events in the 0.6 to 2.2 GHz range correspond to the same intrinsic peak frequency at the emission time ($\nu_0=2.42 \text{ GHz}$ for $m_a = 10 \mu\text{eV}$), which could provide further support for our dense axion star resonant conversion scenario. Since in addition to some surviving axion stars, a diffuse axion component is likely to still account for a large fraction of the DM density, the laboratory measurements from axion haloscope and weak radio signals of axion DM by SKA can cover same frequency range. In parallel with these efforts, SKA is expected to observe many more FRBs, and might allow to pin down the correlation between FRBs, axions in galactic halos, and axions detected in a terrestrial laboratory.

ACKNOWLEDGMENTS

We are grateful to Shmuel Nussinov for enlightening discussions and critical comments on the manuscript. We also thank Raymond Co, Jonathan Katz, Oriol Pujol`as and Yicong Sui for useful discussions, and Yurong Zhao for the schematic manga. The work of JB, BD and FF is supported in part by the U.S. Department of Energy under Grant No. [de-sc0017987]. FPH is supported in part by the McDonnell Center for the Space Sciences.
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