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CONVERSION OF DARK MATTER AXIONS TO PHOTONS IN MAGNETOSPHERES OF NEUTRON STARS

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We propose a new method to detect observational appearance of dark matter axions. The method utilizes radio observations of neutron stars. It is based on the conversion of axions to photons in strong magnetic fields of neutron stars (the Primakoff effect). If the conversion occurs, the radio spectrum of the object has a very distinctive feature — a narrow spike at the frequency corresponding to the rest mass of the axion. For example, if the coupling constant of the photon–axion interaction is $M = 10^{10}$ GeV, the density of dark matter axions is $\rho = 10^{-24}$ g $\cdot$ cm^{-3}, and the axion mass is $5\,\mu$eV, then the flux from a strongly magnetized (10^{14} G) neutron star at the distance 300 pc from the Sun is expected to be about few tenths of mJy at the frequency about 1200 MHz in the bandwidth about 3 MHz. Close-by X-ray dim isolated neutron stars are proposed as good candidates to look for such radio emission.

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1. INTRODUCTION

Most of the matter in the Universe is "dark", i. e., cannot be observed directly by astronomical observations because the particles that form it are not baryons [1, 2]. Many types of new particles were suggested theoretically to explain the dark matter problem. One of the best candidates with a strong theoretical background is the axion — a light neutral pseudoscalar particle that appears in a spontaneous breaking of the Peccei–Quinn symmetry [3] as a solution of the strong CP problem.

In fact, axions are not really dark. In an external electromagnetic field, they can couple to virtual photons and produce real photons (the so-called Primakoff effect [4])

$$a + \gamma_{virt} \to \gamma. \tag{1}$$

Several experiments that utilize the Primakoff effect are underway now. One direction of such studies is to look for an effect related to the conversion of high-energy axions from the interior of the Sun in strong magnetic fields in a laboratory [5, 6]. Solar axions can also be sought in X-ray observations because of the conversion of these particles in the Earth magnetic field [7, 8]. All these experiments are searching for "hot" and "young" axions, not "cold" cosmological particles originated in the early Universe. Here, we propose an astronomical method to detect emission due to the conversion of cosmological axions. Direct experimental searches for such axions are now also in progress in laboratories [9].

The strongest magnetic fields known can be found in the surroundings of neutron stars; under certain conditions, axions that constitute cosmological dark matter can therefore experience the Primakoff effect in magnetospheres of neutron stars. Possible use of such superstrong magnetic fields for searching light pseudoscalar bosons in photon conversion processes was previously discussed in several papers [10, 11]. In what follows, the possibility of detecting photons from such conversion is studied.

2. THEORETICAL MODEL

The axion–photon coupling is given by the term

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$$L_{\gamma\phi} = -\frac{1}{4M} F^{\mu\nu} \tilde{F}_{\mu\nu} \phi \tag{2}$$

in a Lagrangian, where ϕ is the axion field strength, $F^{\mu\nu}$ and $\tilde{F}_{\mu\nu}$ are electromagnetic field strength tensor and its dual tensor, and $1/4M$ is the coupling constant.

The axion rest mass is assumed to be small due to the cosmological and astrophysical constraints $10^{-6}\,\mathrm{eV} \le m_a \le 10^{-2}\,\mathrm{eV}$, and the coupling constant is also small: $M > 10^{10}$ GeV [12, 13].

The conversion probability in a transverse magnetic field B is [14][1)]

$$P_\gamma(L) = 2\left(\frac{B}{2M}\right)^2 \left[\frac{1-\cos qL}{q^2}\right], \tag{3}$$

where

$$q = \frac{|m_\gamma^2 - m_a^2|}{2E_a} \tag{4}$$

is the axion–photon momentum difference,

$$m_\gamma = 0.37\sqrt{n/10^8\ \mathrm{cm}^{-3}}\,\mu\mathrm{eV} \tag{5}$$

is the plasma mass of a photon, and m_a and E_a are the rest mass and the energy of the axion.

We estimate the probability of the conversion of dark matter axions to photons in the magnetosphere of a neutron star using several simplifying assumptions: 1) the velocity of a neutron star relative to axions is perpendicular to its rotation axis (dispersion of axions velocities can be neglected due to its small value [9]); 2) the r-dependence of the magnetic field of a neutron star can be described by the relation

$$B(r) = B_0 \frac{r_0^3}{r^3},$$

where B_0 is the magnetic field strength on the surface of the neutron star and r_0 is its radius.

The flux from the axion–photon conversion changes with the period equal to half the spin period of the neutron star because the dipole axis is perpendicular to the axion flow twice during one revolution.

If the plasma mass of a photon is equal to zero, the conversion is severely suppressed. However, the density of charged particles in the neutron star magnetosphere is quite high, and this makes the conversion possible. For our estimates, we use the Goldreich–Julian (GJ) density. There are claims that the plasma density in the region of closed field lines of highly magnetized stars — magnetars — can exceed the GJ density by several orders of magnitude [15]. This is related to the fact that magnetars have hard tails in their spectra, discovered thanks to observations aboard the Integral satellite (see [16] and the references therein). On the other hand, X-ray dim isolated neutrons stars (also known as "The Magnificent Seven", see below), which we discuss in this paper as prominent candidates, do not have such hard tails, and we therefore suppose that we can securely set the value of the plasma density in the case of the Magnificent Seven equal to the GJ density [17]:

$$n_{GJ} = 7 \cdot 10^{-2} \frac{B}{T}\,\mathrm{cm}^{-3}, \tag{6}$$

where T is the spin period of a neutron star (in seconds), B is the magnetic field (in Gauss),

$$n(r) = \alpha_1 B(r) T^{-1} = \alpha_1 B_0 r_0^3 r^{-3} T^{-1},$$

$\alpha_1 = 7 \cdot 10^{-2}\,\mathrm{s}\cdot\mathrm{cm}^{-3}\cdot\mathrm{G}^{-1}$.

Therefore, the photon plasma mass depends on the radius as

$$m_\gamma(r) = \alpha_2\sqrt{n(r)} = \alpha_1^{1/2}\alpha_2 B_0^{1/2} r_0^{3/2} r^{-3/2} T^{-1/2},$$

where $\alpha_2 = 3.7\cdot 10^{-11}\,\mathrm{cm}^{3/2}\mathrm{eV}$. The conversion occurs when the photon plasma mass coincides with the rest mass of the axion, $m_a = m_\gamma$.

The critical radius r_c and the critical magnetic field $B_c(r_c)$ can be derived from the condition $m_\gamma = m_a$, whence

$$r_c = \alpha_1^{1/3}\alpha_2^{2/3} B_0^{1/3} T^{-1/3} m_a^{-2/3} r_0, \tag{7}$$

$$B_c = \alpha_1^{-1}\alpha_2^{-2} m_a^2 T. \tag{8}$$

For cold axions ($E_a \approx m_a$, see [9]), the relation

$$q = \frac{|m_\gamma^2 - m_a^2|}{2E_a} \approx |m_\gamma - m_a| \equiv \Delta m \tag{9}$$

holds.

The difference between the photon plasma mass and the axion mass depends on the length L of axion path near the critical point (the conversion radius) before the conversion occurs:

$$\Delta m \approx \left|\frac{dm_\gamma(r_c)}{dr} L\right| = \frac{3m_\gamma(r_c)}{2r_c} L.$$

On the other hand, the length L can be determined from the condition of maximum probability (3):

$$qL = \pi. \tag{10}$$

1) In Eqs. (3), (10), and (11), we use the Planck system of units, where energy has the dimension of inverse length.

As a result, we have

$$q^2 = \frac{3\pi}{2}\frac{m_a}{r_c} \qquad (11)$$

After rewriting the expression for the conversion probability

$$P_\gamma = B_c^2 M^{-2} q^{-2}$$

using (7), (8), and (10), we obtain

$$P_\gamma \approx 20\ \mathrm{G}^{-2}\cdot\mathrm{cm}^{-1}\cdot\mathrm{eV}^3 \frac{2}{3\pi}\alpha_1^{-5/3}\alpha_2^{-10/3}\times \\ \times B_0^{1/3}T^{5/3}r_0 m_a^{7/3}M^{-2}, \qquad (12)$$

where the coefficient 20 $\mathrm{G}^{-2}\cdot\mathrm{cm}^{-1}\cdot\mathrm{eV}^3$ is needed to adjust Eq. (3) written in the Planck system of units to the system used in the end of the calculation. The total flux of photons also depends linearly on the critical radius r_c because the amount of axions propagating through the region of active conversion increases linearly with an increase in the critical radius. Finally, we can therefore write our estimate for the amount of energy that comes from the conversion in one second:

$$\dot{E} \propto \alpha_2^{-8/3}\alpha_1^{-4/3}B_0^{2/3}T^{4/3}r_0^2 m_a^{5/3}M^{-2}. \qquad (13)$$

It is clear that the probability increases sharply with an increase in the neutron star spin period and the rest mass of the axion. But there are bounds on B_c [2)] and r_c (it cannot be less than the neutron star radius), and we should therefore specify our candidates for observations for future estimates.

3. POSSIBILITY OF OBSERVATION

For the estimates in what follows, we assume the range of axion rest masses $0.1\ \mu\mathrm{eV} < m_a < 10\ \mu\mathrm{eV}$.

Using Eqs. (6) and (5) we can obtain the relation

$$B_c = 10^{10} T\left(\frac{m_a}{1\mu\mathrm{eV}}\right)^2\ \mathrm{G}. \qquad (14)$$

After substitution of typical values of the axion rest mass and neutron star parameters in the equation for conversion probability (12), it follows that the conversion occurs only for magnetic fields $B_c > 10^{11}$ G, and we therefore need a neutron star with a strong magnetic field. It is also favorable to have a neutron star situated close to the Solar system with the spin period as large as possible.

In our opinion, the best candidates to produce an observable signal due to the axion conversion are X-ray dim isolated neutron stars. Seven objects of this type are known; they are called the Magnificent Seven (M7), and we use this term below (see a review on isolated neutron stars in [18]). They have very strong magnetic fields (up to 10^{14} G) and are located not far from the Solar system (~ 300 pc [19][3)]). Their present evolutionary state is not known: we do not know whether the M7 sources are similar to normal pulsars or have already passed this evolutionary stage and therefore do not produce radio-pulsar-like emission. We use the Goldreich–Julian density of charged particles in a magnetosphere for our estimates. If the density is significantly higher than the Goldreich-Julian value (about such possibility see, e. g. [21]), the conversion is greatly depressed (see Eq. (12)) because it occurs in area with a low magnetic field strength and therefore the probability of conversion is very tiny.

Hence, we let the magnetic field on the surface of a neutron star be equal to 10^{14} G, the spin period equal to 10 s, and the distance from the Earth equal to 300 pc. For $m_a = 5\,\mu$eV, we have

$$B_c \approx 2.5\cdot 10^{12}\,\mathrm{G},$$

$$r_c = 3.4 r_0,$$

$$q^2 = \frac{3\pi m_a}{2 r_c} = 1.3\cdot 10^{-16}\,\mathrm{eV}^2,$$

$$P_\gamma \approx 0.2.$$

It is essential to estimate the total mass of axions that fly through the zone of active conversion ($r < r_c$) per unit time to obtain estimates for the energy of electromagnetic waves from the conversion [22]:

$$\dot{m} = 2\pi(r_c - r_0)GM_{NS}\rho v^{-1}, \qquad (15)$$

where ρ is the axion density, v is the neutron star velocity relative to dark matter, and M_{NS} is the neutron star mass. Density of the dark matter ρ (and therefore the density of axions) is set equal to $10^{-24}\,\mathrm{g}\cdot\mathrm{cm}^{-3}$ [9] (the density may be smaller because such large values can appear only if the source is in a caustic, but because the flux depends on it linearly, it can be easily recalculated with any value of the axion density), the velocity is set equal to $v = 100\,\mathrm{km}\cdot\mathrm{s}^{-1}$, and we use the mass $M_{NS} = 1.4 M_\odot$ and the radius $r_0 = 10$ km. The

2) Soft gamma repeaters are neutron stars with the strongest known magnetic fields, $B \sim 10^{14-15}$ G. Fields of the most magnetized pulsars do not exceed few$\times 10^{13}$ G. There is no evidence of the existence of neutron stars with fields stronger than 10^{15} G (although the physical limit of the field strength is about 10^{18} G).

3) The closest object RX J1856.5-3754 is located at about 170 pc [20].

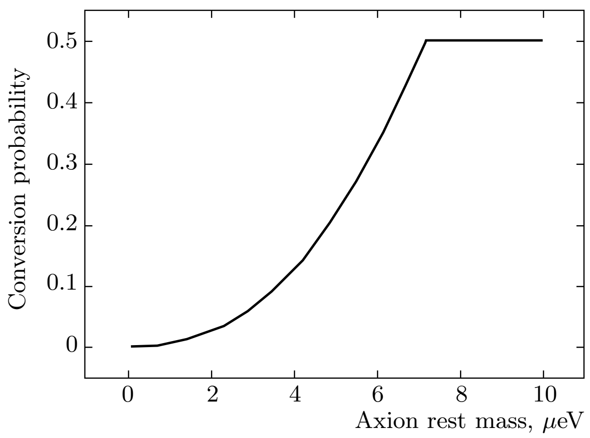

Fig. 1. Conversion probability vs. the axion rest mass. The probability P increases with the mass increase. Saturation occurs at $P = 0.5$ because of the process of the reverse axion–photon conversion that effectively suppresses a further increase in P. Here and in the other figures, the magnetic field on the surface of neutron star is equal to 10^{14} G, the spin period is equal to 10 s, and the distance from the Earth is set to 300 pc

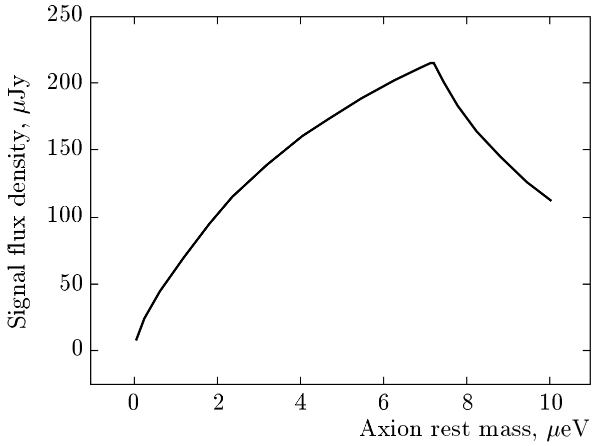

Fig. 2. Flux density of the signal that comes from the conversion of axions of a certain rest mass

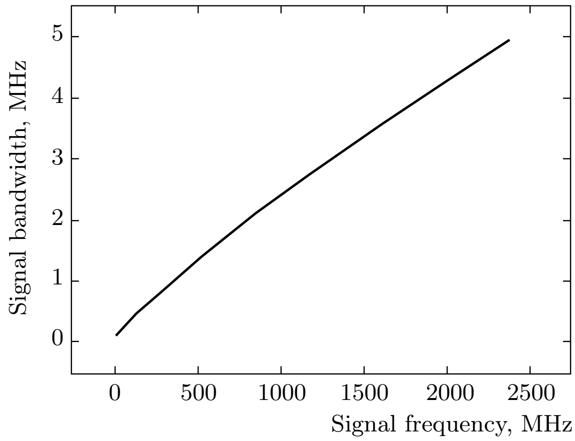

Fig. 3. Bandwidth of the possible signal from the conversion vs. the frequency of observation (the axion rest mass). The bandwidth is defined by the magnitude of the axion–photon momentum difference $q(f)$ from Eqs. (9) and (10), $q^2 \propto f^{5/6}$

total mass of axions propagating through the "active" region per second is

$$\dot{m} = 2.8 \cdot 10^2 \,\mathrm{g \cdot s^{-1}}.$$

The energy that comes from the conversion every second can be estimated as

$$\dot{E} = P_\gamma \dot{m} c^2 = 5.4 \cdot 10^{22} \,\mathrm{erg \cdot s^{-1}}.$$

The electromagnetic flux at 300 pc from a source might be $5 \cdot 10^{-21}\,\mathrm{erg \cdot cm^{-2} \cdot s^{-1}}$. Radio waves would have frequencies near the central frequency corresponding to the axion rest mass m_a, $f_0 = 1200$ MHz in the bandwidth

$$\delta f = f_0 q / m_a = 2.8 \text{ MHz}.$$

The density of that flux might be equal to 0.2 mJy.

We estimated the values of the axion rest mass between 0.1 μeV and 10 μeV. The conversion probability rapidly increases with an increase in the axion rest mass and reach the saturation value $P = 0.5$ at $m_a \approx 7 \mu$eV (Fig. 1). The predicted observable flux has a sharp peak at that value of axion rest mass and then steeply decreases (Fig. 2). The bandwidth of the signal from the conversion smoothly increases with increasing the axion rest mass (Fig. 3).

The estimates above are only upper limits. We do not take the dipole structure of the magnetic field into account:

$$B(\mathbf{n}, r) = \frac{3\mathbf{n}(\mathbf{n} \cdot \mathbf{m}) - \mathbf{m}}{r^3}, \tag{16}$$

where $\mathbf{n}$ is the unit vector along the radius vector $\mathbf{r}$ and $\mathbf{m}$ is the magnetic dipole vector. Accurate estimates with an exact configuration of the magnetic field can slightly reduce our predictions for the flux. Also, the flux might be smaller because of the reverse conversion, but these questions require a detailed study of individual cases, and we do not discuss them here.

It is necessary to mention the possibility of the absorption of photons due to their propagation in high-density plasma near a neutron star surface. Indeed, the electromagnetic waves of a certain frequency

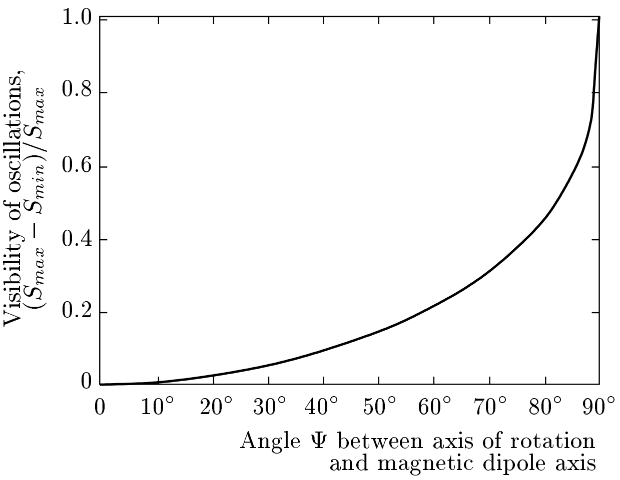

Fig. 4. Dependence of the variability of the flux on the angle Ψ between the rotation axis and the magnetic dipole axis

cannot propagate through regions where the plasma frequency exceeds the electromagnetic wave frequency. In the case of a neutron star that moves through an axion flow away from the Earth, converted photons are reflected by the magnetosphere such the sought signal is weakened. In the opposite case, dense plasma acts as a mirror, sending converted photons to the Earth, thus boosting the signal (it might be confined to a solid angle less than 4π).

The conversion probability could be further decreased by the effect of vacuum polarization [11]. However, the magnetic field strength in the region of active conversion is well below the critical value $5 \cdot 10^{13}$ G. The variability of the signal depends on the angles Ψ and Φ between the spin and magnetic axes and between the spin axis and the velocity vector of a neutron star.

In general, the flux variability with time is very complicated and must be studied numerically. Figure 4 represents the dependence of the flux variability amplitude

$$A = \frac{S_{max} - S_{min}}{S_{max}}$$

on the angle Ψ when the relative velocity of the neutron star to axions is perpendicular to its rotation axis.

It is easy to see that the variability is significant for the angles close to 90° ($P > 0.5$ if $\Psi > 80°$) and does not usually exceed 0.1. The period of variation might be twice shorter than the spin period of the neutron star.

At the moment, the most stringent upper limits on the radio emission from the M7 are given in [23]. At the frequency 820 MHz, the limit is about 10 mJy. At lower frequencies, the situation is less clear. The group from Pushchino [24] announced detection of pulsed emission from two neutron stars belonging to the M7. On the other hand, recent observations with Giant Metrewave Radio Telescope [25] do not confirm it. In the near future, LOFAR observations [26] will become availabe for putting better limits or for detecting the signal due to the axion–photon conversion. The signal from the conversion will be strongly depolarized because the magnetic field direction is different in various parts of the active conversion region.

4. CONCLUSIONS

We suggest to use radio observations of close-by X-ray dim cooling isolated neutron stars to search for observational appearances of dark matter axions. If the axion–photon conversion in the neutron star magnetic field occurs, the radio spectrum of the object might have a very distinct feature — a narrow spike at the frequency corresponding to the axion rest mass. If the coupling constant of the photon–axion interaction is $M = 10^{10}$ GeV, the density of dark matter axions is $\rho = 10^{-24}\,\mathrm{g \cdot cm^{-3}}$ and a neutron star with $B \sim 10^{14}$ G is located at the distance of 300 pc from the Solar system, then the flux density of the signal for axions with the rest mass of $5\,\mu$eV is as large as several tenths of mJy at the frequencies about 1200 MHz in the bandwidth about 3 MHz.

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