PHYSICAL REVIEW D **91**, 023008 (2015)

Axion stars and fast radio bursts

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(Received 17 October 2014; published 22 January 2015)

We show a possible origin of fast radio bursts. They arise from the collisions between axion stars and neutron stars. The bursts are emitted in atmospheres of the neutron stars. The observed frequencies of the bursts are given by the axion mass m_a such as $m_a/2\pi \simeq 2.4\ \text{GHz}(m_a/10^{-5}\ \text{eV})$. By the comparison of the theoretical with observed event rate $\sim 10^{-3}$ per year in a galaxy, we can determine the mass $\sim 10^{-12} M_\odot$ of the axion stars. The mass is identical to the one estimated as the masses of axion miniclusters. Using these values, we can explain short durations (∼ms) and amount of radiation energies ($\sim 10^{43}$ GeV) of the bursts.

DOI: 10.1103/PhysRevD.91.023008 PACS numbers: 98.70.-f, 11.27.+d, 14.80.Va, 98.70.Dk

Fast radio bursts (FRBs) have recently been discovered [1–3] at around 1.4 GHz frequency. The durations of the bursts are typically a few milliseconds. The origin of the bursts has been suggested to be extragalactic owing to their large dispersion measures. This suggests that the large amount of the energy $\sim 10^{46}$ GeV/s is produced at the radio frequencies. The event rate of the burst is estimated to be $\sim 10^{-3}$ per year in a galaxy. Furthermore, no gamma ray bursts associated with the bursts have been detected. To find progenitors of the bursts, several models [4] have been proposed.

In the paper, we show a possible origin of FRBs. They arise from the collisions between neutron stars and axion stars [5,6]. The axion star is a boson star (known as oscillaton [7]) made of axions bounded gravitationally. The axion stars have been discussed [8] to be formed in an epoch after the period of equal matter and radiation energy density. These axion stars are condensed objects of axion miniclusters [8]. The miniclusters have been shown to be produced after the QCD phase transition and to form the main component of dark matter in the Universe.

The production mechanism of FRBs is shown in the following. Under strong magnetic fields of neutron stars, axion stars generate oscillating electric fields [9]. When they collide with the neutron stars, the oscillating electric fields rapidly produce radiations in the atmospheres of the neutron stars. This is because the atmospheres contain dense free electrons. Since the frequency of the oscillating electric field is given by the axion mass m_a, the frequency of the radiations produced [10] in the collisions is equal to $m_a/2\pi \simeq 2.4\ \text{GHz}(m_a/10^{-5}\ \text{eV})$ at the rest frame of the axion stars. The frequency is affected by cosmological and gravitational redshifts. We need to take into account Doppler effects owing to the relative velocities when the neutron stars pass through the axion stars, in order to explain the finite bandwidth of the observed FRBs.

The observations of FRBs constrain the parameters of the axion stars, that is, the mass of the axion and the mass of the axion stars. The observed frequency ($\simeq 1.4$ GHz) of FRBs gives the mass ($\sim 10^{-5}$ eV) of the axion, while the observed rate of the bursts ($\sim 10^{-3}$ per year in a galaxy) gives the mass ($\sim 10^{-12} M_\odot$) of the axion stars under the assumption that the halo of a galaxy is composed of the axion stars. Then, with the use of the theoretical formula [6,9] relating radius R_a to mass M_a of the axion stars, we can find the radius $R_a \sim 10^2$ km. Since the relative velocity v_c at the time when the collisions occur is estimated to be $100,000$ km/s, we find that the durations of FRBs are given by R_a/v_c being of the order of milliseconds. It should be stressed that the mass $\sim 10^{-12} M_\odot$ of the axion stars obtained in our phenomenological analysis is almost identical to the one estimated previously as the masses of axion miniclusters. The axion miniclusters have been shown to form a dominant component of dark matter and to condense to axion stars by gravitationally emitting their kinetic energies [6,7].

First, we explain the classical solutions of the axion stars obtained in previous papers [6,9–11]. The solutions are found by solving classical equations of axion field $a(\vec{x},t)$ coupled with gravity. Assuming the axion potential such that $V_a = -f_a^2 m_a^2 \cos(a/f_a) \simeq -f_a^2 m_a^2 + m_a^2 a^2/2$ for $a/f_a \ll 1$, we approximately obtain spherical symmetric solutions,

$$a(\vec{x},t) = a_0 f_a \exp\left(-\frac{r}{R_a}\right) \sin(m_a t), \qquad (1)$$

with $r = |\vec{x}|$, where m_a and f_a denote the mass and decay constant of the axion, respectively. The solutions represent boson stars made of the axions bounded gravitationally, named as axion stars. We should note that the configurations oscillate with frequency $m_a/2\pi$. (It is well known that real scalar fields coupled with gravity such as the axion field have no static solutions.) The solutions are only valid for the axion stars with small masses $M_a \ll 10^{-5} M_\odot$. The radius R_a of the axion stars is numerically given in terms of the mass M_a by

$$R_a = \frac{m_{\rm pl}^2}{m_a^2 M_a} \simeq 260 \text{ km}\left(\frac{10^{-5}\text{ eV}}{m_a}\right)^2 \left(\frac{10^{-12}M_\odot}{M_a}\right), \quad (2)$$

with the Planck mass $m_{\rm pl}$. The coefficient a_0 is given by

$$a_0 \simeq 0.9 \times 10^{-6}\left(\frac{10^2 \text{ km}}{R_a}\right)^2 \frac{10^{-5}\text{ eV}}{m_a}. \quad (3)$$

Thus, the condition $a/f_a \ll 1$ is satisfied for the axion stars with small mass $M_a \sim 10^{-12}M_\odot$. Although we have used the mass $10^{-12}M_\odot$ for reference, the mass is the one we obtain in the present paper. We note that the maximum mass $M_{\rm max}$ of the stable axion stars is given [11] such that $M_{\rm max} \sim 0.6 m_{\rm pl}^2/m_a \simeq 0.5 \times 10^{-5}M_\odot (10^{-5}\text{ eV}/m_a)$. Thus, the solutions represent stable axion stars. (When we take into account the quartic term $\propto m_a^2 a^4/f_a^2$ in the axion potential V_a, the term becomes comparable to the mass term $m_a^2 a^2$ for the axion stars approximately with masses larger than $10^{-12}M_\odot$. This implies that our solutions approximately hold for the axion stars with the small masses.)

The solutions as well as the parameters R_a and a_0 can be easily found [6,11] for the axion stars with such small masses. In particular, the field configuration of the axion can be interpreted as a wave function of the axion bounded by the gravitational force of the axion stars. Then, the wave function $a(t,r)$ may take the form $a(t,r) = a_0 f_a \sin(\omega t)\exp(-kr)$ with the energy eigenvalue $\omega = \sqrt{m_a^2 - k^2} \simeq m_a - k^2/2m_a$; k gives the radius of the axion stars, $k = R_a^{-1} \ll m_a$. Obviously, the parameter $k^2/2m_a$ represents a binding energy of the axion that is roughly equal to $Gm_a M_a/R_a$ with the gravitational constant G. Thus, we obtain the radius $R_a \sim m_{\rm pl}^2/2m_a^2 M_a$ given in Eq. (2). Furthermore, the mass M_a of the axion stars is approximately equal to the energy of the axion field $M_a = \int d^3x((\vec{\partial}a)^2 + m_a^2 a^2)/2 \simeq \int d^3x m_a^2 a^2/2 \simeq \pi m_a^2 a_0^2 f_a^2 R_a^3/4$ where the average is taken in time. Using the relation $m_a \simeq 6 \times 10^{-6}\text{ eV} \times (10^{12}\text{ GeV}/f_a)$, we can obtain the coefficient a_0 given in Eq. (3). In this way, the solutions along with the parameters R_a and a_0 can be approximately obtained. Hereafter, the precise values of these parameters are irrelevant for our discussions below.

Now, we proceed to discuss FRBs arising from the collisions between axion stars and neutron stars. The axion stars generate electric field $\vec{E}_a$ under magnetic field $\vec{B}$ of the neutron stars because the axion couples with both electric field $\vec{E}$ and magnetic field $\vec{B}$ in

$$L_{aEB} = k\alpha \frac{a(\vec{x},t)\vec{E}\cdot\vec{B}}{f_a \pi}, \quad (4)$$

with the fine structure constant $\alpha \simeq 1/137$, where the numerical constant k depends on axion models; typically, it is of the order of 1. Hereafter, we set $k = 1$. From the Lagrangian, we derive the Gauss law, $\vec{\partial}\cdot\vec{E} = -\alpha\vec{\partial}(a\vec{B})/f_a\pi$. Thus, the electric field generated by the axion stars under the magnetic field $\vec{B}$ is given by

$$\vec{E}_a(r,t) = -\alpha\frac{a(\vec{x},t)\vec{B}}{f_a\pi} = -\alpha\frac{a_0\exp(-r/R_a)\sin(m_a t)\vec{B}}{\pi}. \quad (5)$$

The electric field oscillates coherently over the whole of the axion stars. The field induces the coherently oscillating electric currents with large length scale in the atmospheres of the neutron stars. Thus, the large amount of radiation is emitted so that the axion stars loses their energies. As will be shown later, all the energies of a part of the axion stars touching the atmospheres of the neutron stars are released into the radiations. Namely, the neutron stars make the axion stars evaporate into the radiations. The frequency of the radiations is given by $m_a/2\pi \simeq 2.4 \times (10^{-5}\text{ eV}/m_a)$ GHz. Since the collisions take place over a short period $R_a/v_c \sim$ millisecond, we may identify the radiations as the FRBs.

Before estimating how rapidly the axion stars lose their energies, we calculate the rate of the collisions between axion stars and neutron stars in a galaxy. Then, we can determine the mass of the axion stars by the comparison of the theoretical with the observed rate of the bursts. We assume that the halo of a galaxy is composed of the axion stars of which the velocities v relative to neutron stars are supposed to be 3×10^2 km/s. Since the local density of the halo is supposed to be $0.5 \times 10^{-24}\text{ g cm}^{-3}$, the number density n_a of the axion stars is given by $n_a = 0.5 \times 10^{-24}\text{ g cm}^{-3}/M_a$. The event rate $R_{\rm burst}$ can be obtained as

$$R_{\rm burst} = n_a \times N_{\rm ns} \times Sv \times 1 \text{ year}, \quad (6)$$

where $N_{\rm ns}$ represents the number of neutron stars in a galaxy; it is supposed to be 10^9. We use the standard formula of the cross section S for the collision given by $S = \pi(R_a + R)^2(1 + 2G(1.4M_\odot)/v^2(R_a + R))$ where $R(= 10\text{ km})$ denotes the radius of a neutron star with mass $1.4M_\odot$. Then, it follows that the observed event rate is given by $R_{\rm burst} \sim 10^{-3} \times (0.2 \times 10^{-11}M_\odot/M_a)^2$ per year in a galaxy when we take $M_a = 0.2 \times 10^{-11}M_\odot \sim 10^{-12}M_\odot$. The radius of the axion stars with the mass is approximately equal to 10^2 km, which is much larger than that of the neutron star. Thus, when the collisions take place, the neutron stars pass through the insides of the axion stars. Then, the collisons convert the axion energies to the radiation energies given by $0.2 \times 10^{-11}M_\odot(10\text{ km}/10^2\text{ km})^2 \sim 10^{43}$ GeV. Thus, we can explain the observed energies of the FRBs. It should be stressed that the mass $10^{-12}M_\odot$ of the axion stars is the one estimated previously as the masses of axion miniclusters [12].

We would like to mention the finite bandwidth of the observed frequencies. The frequency of the electric field on the axion stars observed at the rest frame of the neutron stars changes in the collision owing to Doppler effects. The relative velocity is given by $v_e \simeq \sqrt{2G \times 1.4M_\odot/(R+R_a)} \simeq 2 \times 10^{-1}$ when the neutron stars touch the edge of the axion stars, while it is given by $v_c \simeq \sqrt{2G \times 1.4M_\odot/R} \simeq 6 \times 10^{-1}$ when the neutron stars go through the centers of the axion stars. Thus, the frequencies of radiations emitted in the atmospheres of the neutron stars vary in the process of the collisions. This fact causes the finite bandwidth of the observed frequencies in our production mechanism of FRBs.

Now, we estimate how rapidly the axion stars emit radiations in the collisions with neutron stars. In particular, we show that they rapidly lose their energies in the atmospheres of neutron stars with temperature $\sim 10^5$ K assumed. (Almost of all neutron stars present in a galaxy are old and may have a temperature of the order of $\sim 10^5$ K.) The electric field $\vec{E}_a$ in Eq. (5) generated under the magnetic field makes an electron with momentum $\vec{p}$ oscillate according to the equation of motion $\dot{p} = eE_a$ where we write down the component of the equations parallel to the magnetic field $\vec{B}$. Namely, the direction of the oscillation is parallel to $\vec{B}$. The electron emits a dipole radiation. The emission rate of the radiation energy is given by $2e^2\dot{p}^2/(3m_e^2)$ with electron mass m_e. When the number of electrons emitting the radiations is N_e, the total emission rate is given by $2N_e e^2\dot{p}^2/(3m_e^2)$. However, the oscillations of electrons in the axion star are coherent so that the total amount of radiation energy produced by the coherent oscillations is given by $2e^2\dot{p}^2N_e^2/(3m_e^2)$. The number N_e of the coherent electrons is given such that $N_e \sim n_e\lambda^3$ with electron density n_e, where $\lambda = 2\pi/m_a \simeq 12\ \mathrm{cm}(10^{-5}\ \mathrm{eV}/m_a)$ represents the wavelength of the radiations. That is, electrons at least within the volume λ^3 oscillate coherently. When the atmosphere is thinner than the wavelength, N_e is given such that $N_e = n_e d\lambda^2$, where d is the depth of the atmosphere. Actually, the depth is at most 1 cm for such old neutron stars with temperature 10^5 K.

We wish to make a comment that the thermal effects of the electron gas under consideration do not affect the oscillation induced by the electric field. Since the temperature of the atmospheres of neutron stars is assumed to be of the order of 10^5 K, kinetic energies ~ 10 eV of the electrons are much smaller than the kinetic energy of the oscillation, $p^2/2m_e = (eE)^2/2m_e m_a^2 \sim 10^2(B/10^{10}\ \mathrm{G})^2$ eV with $m_a = 10^{-5}$ eV.

We proceed to discuss coherent radiations emitted from a region with the volume $d\lambda^2 \sim 1 \times 10^2\ \mathrm{cm}^3(10^{-5}\ \mathrm{eV}/m_a)^2$ in the atmosphere of neutron stars. Since the depth $d = 1$ cm is much smaller than the wavelength $\lambda \sim 10$ cm, the radiations emitted in the atmosphere can escape from the atmospheres. Then, we obtain the emission rate $\dot{W}$ of the radiation energy from the region,

$$\dot{W} = \frac{2(e\dot{p}N_e)^2}{3m_e^2} = \frac{2N_e^2}{3}\frac{e^2\alpha^2 a_0^2 B^2}{\pi^2 m_e^2} \sim 10^{-9} N_e^2\ \mathrm{GeV/s}\left(\frac{B}{10^{10}\ \mathrm{G}}\right)^2 \sim 10^{37}\ \mathrm{GeV/s}\left(\frac{n_e}{10^{21}\ \mathrm{cm}^{-3}}\right)^2\left(\frac{B}{10^{10}\ \mathrm{G}}\right)^2, \qquad (7)$$

where the number of electrons N_e in the region is

$$N_e = 10^2\ \mathrm{cm}^3 n_e = 10^{23}\left(\frac{n_e}{10^{21}\ \mathrm{cm}^{-3}}\right), \qquad (8)$$

where we have taken as an example the number density $n_e = 10^{21}/\mathrm{cm}^3$ of electrons, which is realized in the hydrogen atmospheres with the density $\sim 10^{-3}\ \mathrm{g/cm}^3$ when they are fully ionized. (The density at the bottom of the atmosphere may be larger than $1\ \mathrm{g/cm}^3$. Thus, the region in which the radiations are emitted is the upper region of the atmospheres.) On the other hand, the energy of the axion star contained in the volume $10^2\ \mathrm{cm}^3$ is given by $0.2 \times 10^{-11} M_\odot(10^2\ \mathrm{cm}^3)/(4\pi R_a^3/3) \sim 10^{25}$ GeV. The energy is smaller than the energy of the radiations $\dot{W} \times (d/v_c \sim 10^{-10}\ \mathrm{s}) \simeq 10^{27}$ GeV emitted within the time $d/v_c \sim 10^{-10}$ s that it takes for the axion star to pass the depth L of the atmosphere. (v_c denotes the relative velocity at the collision between axion stars and neutron stars; $v_c = \sqrt{2G(1.4M_\odot)/(R+R_a)} \simeq 6 \times 10^4\ \mathrm{km/s}$.) It implies that the axion energy is immediately transformed into the radiation energy. Therefore, we find that the axion stars lose their energies by emitting the radiations near the surfaces of the neutron stars. It is notable that the total amount of the radiation energy $0.2 \times 10^{-11} M_\odot(10\ \mathrm{km}/10^2\ \mathrm{km})^2 \sim 10^{43}$ GeV produced in the collision is coincident with the observed one. Furthermore, it takes $10^2\ \mathrm{km}/v_c \sim 1$ ms for the neutron star to pass the axion star. This gives the observed durations of the FRBs.

Therefore, comparing the theoretical formulas of the axion stars with the observed values of the FRBs, we find that our production mechanism of RFBs is promising. It is remarkable that we can determine the mass of the axion by observing the frequencies of FRBs. The axion mass $\simeq 10^{-5}$ eV we obtain is in the window allowed by observational and cosmological constraints [13].

The author expresses thanks to Prof. J. Arafune for useful comments and discussions. After the submission of the paper we, found a paper [14] discussing a production mechanism of the FRBs using axion miniclusters.

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