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Explanation of Detailed Spectral Properties of FRBs by Axion Star Model

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We have proposed a generation mechanism of non repeating (repeating) fast radio bursts: They arise by axion star collisions with neutron stars (accretion disks of galactic black holes). The axion star as coherent state of axions with mass m_a generates homogeneous electric field oscillating with frequency $m_a/2\pi$ under strong magnetic fields. The field makes electrons coherently oscillate and emit the coherent dipole radiations (FRBs). The radiations stop when the oscillations are disturbed by thermal fluctuations produced by the themalization of the oscillating energies. Thus, the durations of the FRBs are determined by the time scale of the thermalization. We show that it is much shorter than 1ms. Line spectra of the dipole radiations are broadened by the thermal effects. The thermally broaden spectra have a feature that the bandwidths $\delta\nu$ are proportional to their center frequencies ν_c; $\delta\nu \propto \nu_c$. Because the accretion disks can orbit with relativistic velocities, the radiations are Doppler shifted. It leads to the presences of various center frequencies (1.2GHz$\sim$7GHz) in repeating FRB 121102. On the other hand, non repeating FRBs do not show such variety of the center frequencies. They come from the surfaces of neutron stars whose motions are non relativistic. The Doppler shift also makes the durations of the bursts with higher frequencies become shorter. Because the magnetic fields of the neutron stars are supposed to be stronger than those of the accretion disks, the peak flux densities of non repeating FRBs are larger than those of repeating FRB 121102. The strong magnetic fields of the neutron stars also lead to much wide bandwidths of non repeating FRBs, which are over the extent of the receiver frequency range. The spectral features of the recently discovered new repeating FRB 180814.J0422+75 are coincident with our general analyses of the repeating FRB 121102.

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Axion, Fast Radio Burst, Accretion disk

I. INTRODUCTION

Since a Fast Radio Burst (FRB) has been originally reported[1], more than 50 FRBs have been observed. Among them, only a FRB 121102 emit bursts repeatedly[2–5] and so is named as repeating FRB. (CHIME has very recently observed[6] a new repeating FRB 180814.J0422+75.) The detailed follow up observations of the FRB 121102 have been performed. As a consequence, we have obtained detailed spectral and temporal properties of the FRB 121102 in a wide frequency range 1GHz$\sim$8GHz. On the other hand, the other FRBs have not been observed to repeat and so are named as non repeating FRBs. Thus, their observations have been limited only in a frequency range 0.8GHz$\sim$1.6GHz. Although observations [7] at low frequencies 145MHz, 182MHz and 350MHz have been performed, any FRBs have not been detected.

The typical properties common in both types of the FRBs are in the following. The durations are a few milliseconds. They have the large dispersion measures suggesting extra-galactic origins so that the large amount of the energies $\sim 10^{40}$erg/s are produced at the radio frequencies. Additionally, the event rate of non repeating FRBs is approximately $\sim 10^3$ per day at the earth.

These fundamental properties can be explained by many models[8, 9] for sources of FRBs; magnetar, neutron stars merger, highly rotating newly born neutron stars, etc.. To restrict the models, we need to explain spectral and temporal properties of FRBs in detail. Especially, the detailed observations of the repeating FRB 121102 help to select a few models among them.

The follow up observations[10–12] have shown that the FRB 121102 is originated in a dwarf galaxy with redshift $z \simeq 0.19$. The galaxy is conjectured to be an AGN. The bursts of the FRB 121102 have been observed[4, 5, 13, 14] with multiple bands 1.2GHz $\sim$ 1.5GHz, 1.7GHz $\sim$ 2.3GHz, 2.5GHz $\sim$ 3.5GHz, 4.5GHz$\sim$ 5GHz and 4GHz$\sim$ 8GHz. Consequently, we have found that the bursts exhibit finite bandwidths; they are not broadband. Sometimes it is stated that the spectra have structures. But we would like to state that the bursts are narrowband. This is because simultaneous multi band observations clearly show that any repeating bursts have no spectra at lower frequencies $<$ 100MHz and at much higher frequencies $>$ 13GHz. (Our axion model[15, 16] for FRBs predicts that any FRBs exhibit thermally broaden narrow band spectra although they intrinsically exhibit an line spectrum.) In addition, the bursts have no visible light, X ray or gamma ray components[17, 18], which have been confirmed by simultaneous observations. Although there is a possibility of non detections owing to low sensitivities of telescopes for the electromagnetic waves at such low or high frequencies, the observations of the repeating FRB 121102 indicate that the bursts are really narrowband just as molecular line emissions. Our axion model predicts such narrow bandwidths of the non repeating and repeating bursts, although the bandwidths of the non repeating FRBs are much wide to be over the extent of receiver frequency ranges.

Along with the narrow bands of the repeating FRB, the observations exhibit a tendency that the burst widths $\delta\nu$ are proportional to the center frequencies ν_c; $\delta\nu \propto \nu_c$. For instance, we can see bandwidths roughly given by $\sim$ 500MHz at the center frequencies $\sim$ 3GHz[5] and similarly $\sim$ 1GHz at the frequencies $\sim$ 6GHz[13]. It seems that the proportionality holds even for the bursts with the frequencies $\sim$ 2GHz[4] (their bandwidths $\sim$ 300MHz) and 1.3GHz[3] (bandwidths $\sim$ 200MHz). The recent observation[6] by the CHIME shows that the repeating FRB 180814.J0422+75 has bandwidth $\sim$ 100MHz at the center frequency $\sim$ 700MHz.

Furthermore, it is recognized that the peak flux densities of non repeating FRBs are approximately ten times higher than those of repeating FRBs. More interestingly it has recently been pointed out[13] that in the FRB 121102 the durations of the bursts with higher frequencies are shorter than the ones of the bursts with lower frequencies. It seems that the product of the duration and the center frequency is approximately constant; it is independent of the frequencies ν_c. The feature also holds even for the new repeating FRB 180814.J0422+75.

The follow up observations clarify the presence of a persistent radio source spatially coincident with the bursting source of the FRB 121102. The persistent source might be nebula associated with neutron star or AGN. The presence of the persistent source has been considered as a main evidence supporting newly born magnetor model for the FRB 121102.

Rotation measures of FRBs have also been obtained[19, 20]. The radiations of the FRB 121102 are 100% linearly polarized. It is notable that the rotation measures[20] of the FRB 121102 are very large such as $\sim 10^5$rad m^{-2}, while those of the non repeating FRBs are at most $\sim 2\times 10^2$rad m^{-2}. It indicates that the environment of the FRB121102 is similar to the one of PRS J1745-2900 located near the black hole of the Milky Way galaxy, while those of the non repeating FRBs are similar to environments of ordinary pulsars (neutron stars) in the Milky Way galaxy. The observations of the large rotation measure and the persistent source in the vicinity of the source of the FRB 121102 lead to a conjecture that the source of the FRB 121102 might be a newly born magnetar or would be associated with AGN.

These spectral and temporal properties of the repeating FRB 121102 are clue to find sources of the fast radio bursts. In the paper we explain all of the properties by using the axion model[15, 16]; axion star collides with neutron stars (source of non repeating FRBs) and with accretion disks of galactic black holes (source of repeating FRBs like FRB 121102). In the axion model, FRBs are emitted from electron gases in these astrophysical objects which the axion star collides. In particular, accretion disks can orbit with relativistic velocities when they are in the vicinity of the black hole. Thus, we can expect some phenomena associated with Doppler effects. We show that the spectral and temporal properties mentioned above are caused by the Doppler effects. On the other hand, the electron gases of neutron stars move only with non relativistic velocities. The fact leads to non observations of the non repeating FRBs with low frequencies ($<$ 200MHz) or high frequencies ($>$ 3GHz). Probably, magnetic fields of neutron stars are stronger than those of accretion disks. Owing to the fact, peak flux densities of the non repeating FRBs are larger than than those of the repeating FRB. Additionally, it may cause too large bandwidths ($>$ 1GHz) of non repeating FRBs to be detectable; they are over the extent of the receiver frequency ranges. Indeed, their bandwidths have not been detected. (Very recent observation[21] exhibits that spectra of non repeating FRBs have no components with low frequencies. It suggests that the bursts are not broadband like the repeating FRB 121102 and their bandwidths are larger than those of the repeating FRBs with frequencies $\sim$ 1.4GHz.) These detailed spectral and temporal properties mentioned above are not clearly explained by the newly born magnetar (neutron star) model.

(We assume in the paper that the accretion disk is geometrically sufficiently thin in order for the axion star to be able to pass the disk and to collide it several times orbiting a black hole. Such a disk would have much low temperature and have strong magnetic fields $\sim 10^{10}$G. Actually, there is a model[22, 23] of geometrically thin accretion disk with the strong magnetic fields in the vicinity of the black hole. Furthermore, we assume that the dark matter in the Universe is mainly composed of axion stars, which highly condense in the centers of galaxies and frequently collide the accretion disks.)

The axion model predicts coherent emissions at radio frequencies. Additionally, the model predicts some ejecta in the axion star collision with neutron stars or accretion disks. In particular, these ejecta repeatedly take place in the repeating FRB 121102. The ejecta would form the persistent radio source or could power the source observed in the vicinity of the FRB 121102.

The axion stars are coherent states of axions. We present approximate solutions of gravitationally loosely bound states of the axions in the section III. Although they are spherical, actual forms of the axion stars are extremely distorted[24] by tidal forces. But the coherence of the axions is kept because the number of the axions in the volume m_a^{-3} is extremely large such as $\sim 10^{40}$. Our analyses hold even for such non spherical axion stars[16]. This is because the tidal forces do not change the masses of the axion stars and the parameters (especially, the amplitudes of the axion fields) characterizing the axion stars are almost fixed by their masses. These parameters are used for the evaluation of the emission properties of FRBs. Therefore, our spherical solutions themselves presented in section III are not essential for the explanation of various properties of FRBs.

II. COHERENT DIPOLE RADIATIONS

FRBs are coherent radiations because their energy fluxes are extremely large $\sim 10^{40}$erg/s and the sizes of their sources are small $\sim$ 1ms$\times 10^{10}$cm/s $= 10^7$cm. It is expected that they are emitted in environments with strong magnetic fields such as neutron stars. But, it is difficult to make explicit the emission mechanism of coherent radiations associated with the strong magnetic fields. It is believed[9] that some non linear effects in the plasma with strong magnetic fields generate the coherent radiations.

We show that when axion stars collide with magnetized electron gases, the electrons emit coherent dipole radiations. The mechanism[16] is very simple. First, we notice that electrons can coherently emit radiations when they are imposed by spatially homogeneous oscillating electric field $\vec{E}(t) = \vec{E}_0 \cos(m_a t)$. (Such an electric field is generated by axion stars when they are imposed by strong magnetic fields, as we show in next section.) The motion of each electron with electric charge e is described by the momentum $\vec{p}(t) = e\vec{E}_0 \sin(m_a t)/m_a + \vec{p}(t=0)$. Obviously, electrons coherently oscillate and emit dipole radiations with the frequency $m_a/2\pi$. (Electrons in a region where the homogeneous electric field is present can emit coherent radiations.) The radiations are monochromatic and are 100% linearly polarized. The most of the radiations are emitted in the direction perpendicular to the electric field. This is the emission mechanism of the coherent radiations in the axion model. (The conversion of the axions into radio waves in the magnetosphere of neutron star has been discussed[25]. As a result, the radio waves with the frequency ν_{int} are produced. The conversion resonantly arises when the plasma frequency is equal to the frequency ν_{int}. But the radiations are incoherent so that their energies are extremely smaller than the energies of the FRBs or the whole energy of the axion star. Thus, the axion star survives against the conversion even if it passes the regions with the plasma frequencies larger than ν_{int}.)

In general, the coherent oscillations are disturbed by thermal fluctuations. The momenta of the electrons at temperature T are given by $\vec{p}(t) + \vec{p}_{\text{thermal}}$ with $\vec{p}^2_{\text{thermal}}/2m_e = T$ as long as $p(t) \gg p_{\text{thermal}}$; m_e denotes the electron mass. Thus, the coherent oscillations are not disturbed by the thermal fluctuations at low temperatures. But, the temperature of the electron gases increases because the oscillation energies are thermalized. Once the temperature goes beyond a critical one T_c, the coherent oscillations are disturbed so that the coherent radiations stop. Such a critical temperature is approximately given by $T_c \simeq \vec{p}(t)^2/2m_e \simeq (eE_0/m_a)^2/2m_e$. The temperature T_c determines the widths of the thermally broadened spectra of the dipole radiations. We show later that the time scale needed for the thermalization is much less than the observed durations (millisecond) of FRBs.

III. AXION STARS AND GENERATION OF ELECTRIC FIELD

Before showing how the electric fields are generated by axion stars, we explain what is axion or axion star. The axion is the Numbu-Goldstone boson[26] associated with U(1) Pecci-Quinn symmetry. The symmetry is chiral and naturally solves the strong CP problem in QCD: The problem is why the CP violating term $G_{\mu,\nu}\tilde{G}^{\mu,\nu}$ is absent in QCD Lagrangian where $G_{\mu,\nu}$ ($\tilde{G}^{\mu,\nu}$) denotes (dual) fields strength of gluons. (If the exact chiral symmetry is present, the term can be made to vanish. But it is no so because u and d quarks have small bare masses.) Although the axion is described by a real massless scalar field, it acquires its mass m_a through chiral anomaly because the Pecci-Quinn symmetry is chiral. Thus, instantons in QCD give rise to the mass of the axion.

The axions are one of most promising candidates of the dark matter. The axions may form axion stars known as oscillaton[27, 28]; the axion stars are gravitationally bounded states of axions. In the early Universe, axion miniclusters[29] are produced after the QCD phase transition and become the dominant component of the dark matter. After the formation of the axion miniclusters, the axions condense and form axion stars by gravitational cooling[28, 30] as more compact coherent states of axions. In the present paper we assume that the dark matter is mainly composed of the axion stars.

As the axion field is real scalar, there are no static solutions in a system of the axion coupled with the Einstein gravity. Only oscillating solutions are present, which represent oscillating coherent states of the axions. When the mass M_a of the axion star is small enough for the binding energies of the axions to much less than the axion mass m_a, approximate spherical solutions[31] are given by

$$a = a_0 f_a \exp(-\frac{r}{R_a}) \cos(m_a t) \quad \text{with} \quad a_0 = 0.8 \times 10^{-7} \Big(\frac{M_a}{2 \times 10^{-12} M_\odot}\Big)^2 \Big(\frac{m_a}{0.6 \times 10^{-5}\text{eV}}\Big)^3 \tag{1}$$

with the decay constant f_a of the axions, where the radius R_a of the axion stars is approximately given by

$$R_a = \frac{1}{G M_a m_a^2} \simeq 360\text{km} \Big(\frac{0.6 \times 10^{-5}\text{eV}}{m_a}\Big)^2 \frac{2 \times 10^{-12} M_\odot}{M_a} \tag{2}$$

where G denotes the gravitational constant. The decay constant f_a is related with the mass m_a; $m_a \simeq 6 \times 10^{-6}\text{eV} \times (10^{12}\text{GeV}/f_a)$. There are two unknown parameters m_a and M_a (or R_a). The mass M_a (or radius R_a) of the axion star was obtained[15, 32] by comparing the collision rate between neutron stars and axion stars in a galaxy with the event rate of FRBs $\sim 10^{-3}$ per year in a galaxy. It was found that the mass takes a value roughly given by $M_a = (10^{-11} \sim 10^{-12}) M_\odot$. The axion mass m_a is supposed to be $\simeq 0.6 \times 10^{-5}$eV so as for the intrinsic frequency ν_{int} of the non repeating FRBs to be given by $m_a/2\pi \simeq 1.4$GHz. The value is in a window allowed in axion searches. (The observed frequencies ν receive effects of cosmological expansions such that $\nu = \nu_{\text{int}}/(1+z)$ with redshift z.) The spherical solutions represent gravitationally loosely bound states of the axions. They are easily deformed by tidal forces of neutron stars or black holes. The solutions themselves are not used for the estimation of electric fields generated by the deformed axion stars. But the value a_0 can be approximately used for the estimation in the following reason, even if the spherical forms of the solutions are deformed.

The above solutions represent coherent states of the axions possessing much small momentum k given by $k \sim 1/R_a \ll m_a$. The number of the axions in the volume with m_a^{-3} (m_a^{-1} is Compton wavelength of the axion) is extremely large; $M_a/m_a \times (1/R_a m_a)^3 \sim 10^{41}$. It turns out that the coherence is very rigid. That is, the coherence is kept even if tidal forces of neutron stars or black holes distort the shapes of the axion stars like long sticks[24]. It implies that the deformed axion stars can be treated classically just as classical electromagnetic waves. Because the tidal forces do not change the mass M_a of the axion stars, we may approximately estimate the value of $a_0 = a/f_a$ when the axion stars are deformed, by using the formula $M_a = \int d^3x((\partial_t a)^2 + (\vec{\partial}_x a)^2 + (m_a a)^2)/2 \sim (m_a a)^2 \times$ "volume of the axion star". The tidal forces extremely deform the spherical forms and also change the volumes of the axion stars. But even if the volume becomes 10 times larger, the value a only changes to be 3 times smaller. Therefore, we may approximately use the value a_0 in eq(1) of the spherical solutions, in order to estimate the strength of the electric field $\vec{E}$ generated by the axion star collisions with neutron stars or accretion disks.

Now we show how the axion star generates electric field under magnetic fields. It is well known that the axion $a(\vec{x}, t)$ couples with both electric $\vec{E}$ and magnetic fields $\vec{B}$ in the following,

$$L_{aEB} = k_a \alpha \frac{a(\vec{x}, t)\vec{E} \cdot \vec{B}}{f_a \pi} \tag{3}$$

with the fine structure constant $\alpha \simeq 1/137$, where the numerical constant k_a depends on axion models; typically it is of the order of one. Hereafter we set $k_a = 1$. The interaction term slightly modifies Maxwell equations;

$$\begin{aligned}\vec{\partial} \cdot \vec{E} + \frac{\alpha \vec{\partial} \cdot (a(\vec{x}, t)\vec{B})}{f_a \pi} &= 0 \quad , \quad \vec{\partial} \times \Big(\vec{B} + \frac{\alpha \vec{\partial} \cdot (a(\vec{x}, t)\vec{E})}{f_a \pi}\Big) - \partial_t \Big(\vec{E} + \frac{\alpha \vec{\partial} \cdot (a(\vec{x}, t)\vec{B})}{f_a \pi}\Big) = 0, \\ \vec{\partial} \cdot \vec{B} &= 0 \quad , \quad \vec{\partial} \times \vec{E} + \partial_t \vec{B} = 0.\end{aligned} \tag{4}$$

From the equations, we approximately obtain the electric field $\vec{E}$ generated on the axion stars under the background homogeneous magnetic field $\vec{B}$,

$$\begin{aligned}\vec{E}_a(r, t) &= -\alpha \frac{a(\vec{x}, t)\vec{B}}{f_a \pi} = -\alpha \frac{a_0 \exp(-r/R_a) \cos(m_a t) \vec{B}(\vec{r})}{\pi} \\ &\simeq 1.3 \times 10^{-1}\,\text{eV}^2(\simeq 0.7 \times 10^4\text{eV/cm}\,) \cos(m_a t) \Big(\frac{M_a}{2 \times 10^{-12} M_\odot}\Big)^2 \Big(\frac{m_a}{0.6 \times 10^{-5}\text{eV}}\Big)^3 \frac{B}{10^{10}\text{G}} \frac{\vec{B}}{B}.\end{aligned} \tag{5}$$

with $r \ll R_a$, where we have taken into account that the momenta of the axions are vanishingly small; $\vec{\partial} a(\vec{x}, t) \simeq 0$.

This is the electric field discussed in the previous section. It oscillates with the frequency $\nu_{\rm int} = m_a/2\pi$ because the axion field does with the frequency. The electric field makes electrons coherently oscillate over the region with the volume R_a^3 or the region in which magnetic field can be regarded as spatially homogeneous one. Because magnetic fields in accretion disks point in the inside of the disks, the electric fields point in the same direction so that the coherent dipole radiations are emitted outside the disks. On the other hand, the magnetic fields of neutron stars point in the outside of the neutron stars but not necessarily point in the direction just perpendicular to their surfaces. Thus, the dipole radiations can be emitted outside the neutron stars.

Because we obtain the oscillating electric field in eq(5), we estimate the critical temperature T_c discussed in the previous section,

$$T_c = \Big(\frac{eE_0}{m_a}\Big)^2 \frac{1}{2m_e} \simeq 0.5 \times 10^3 \mathrm{eV} \Big(\frac{eB}{10^{10}\mathrm{G}}\Big)^2 \Big(\frac{M_a}{2 \times 10^{-12} M_\odot}\Big)^4 \Big(\frac{m_a}{0.6 \times 10^{-5}\mathrm{eV}}\Big)^4. \tag{6}$$

Coherent radiations emitted from electron gases are terminated at the temperature T_c.

We should mention that the electrons acquire thermal energies (e.g. $T_c \sim 10^3$eV) in the axion star collision with neutron stars or accretion disks. Because such a large amount of the energies is deposited on the surface of the neutron star or accretion disk in a very short time (< 1ms), the clumps of the gases absorbing the energies may flow outside the surface. More importantly, ejecta with much larger energies than those of the clumps in the surface are produced by the axion star collision with the accretion disk. We note that coherent radiations are produced even in deep inside of the neutron stars or the accretion disks. They are absorbed inside the astrophysical objects themselves. The gases absorbing the radiations can be ejected outside the astrophysical objects, in particular, geometrically thin accretion disk. (Only a fraction of the gases absorbing the radiation energies would be ejected from the axion star collisions with neutron stars.) This is because the energies of the radiations are extremely large as we show below and deposited with a very short time less than 1 msec. The ejecta arise repeatedly in the FRB 121102. These ejecta would form the persistent radio source or could power the persistent source observed in the vicinity of the FRB 121102. In the next section we estimate energies and durations of FRBs as well as the energies of the ejecta.

IV. BURST ENERGY AND DURATION

We show that the energies of FRBs can reach 10^{40}erg/s when the axion stars collide neutron stars or accretion disks with strong magnetic fields. Because each electron emits the energy $\dot{w} \equiv e^2\dot{p}^2/3m_e^2 = e^4\vec{E_0}^{\,2}/3m_e^2$ in the oscillating electric field $\vec{E} = E_0\cos(m_a t)$ in eq(5), the electrons in the unit volume 1cm^3 can emit coherent radiations with the energies per unit time,

$$\dot{W} = \dot{w}\bigg(n_e \times 1\mathrm{cm}^3\bigg)^2 \sim 10^{27}\,\mathrm{erg/s}\,\Big(\frac{n_e}{10^{20}\mathrm{cm}^{-3}}\Big)^2 \Big(\frac{M_a}{2 \times 10^{-12} M_\odot}\Big)^4 \Big(\frac{B}{10^{10}\mathrm{G}}\Big)^2, \tag{7}$$

where n_e denotes electron number density assumed to be large such as 10^{20}cm^{-3}.

The radiations are emitted from the surfaces of the neutron stars or accretion disks of galactic black holes. In particular, The emissions arise from thin layers in the surfaces just as the radio emissions from metals. Their thickness is given by the penetration depth λ. Thus, the large amounts of the radiation energies are produced in the regions with their volumes $V_a = (10^4\mathrm{cm})^2 \times 0.1\mathrm{cm}(\lambda/0.1\mathrm{cm})$,

$$\dot{w}(V_a n_e)^2 \sim 10^{27}\mathrm{erg/s}\Big(\frac{(10^4\mathrm{cm})^2 \times 0.1\mathrm{cm}(\lambda/0.1\mathrm{cm})}{1\mathrm{cm}^3}\Big)^2 \sim 10^{41}\mathrm{erg/s}. \tag{8}$$

The penetration depth is sometimes called as skin depth. The depth λ is approximately given using the electric conductivity σ of electron gases such that $\lambda \sim \sqrt{1/\nu_{\rm int}\sigma}$ with $\sigma = \omega_p^2\tau/4\pi$ where $\omega_p = \sqrt{e^2 n_e/m_e}$ denotes the plasma frequency and τ does the mean free time of the electrons. Numerically, they are given by $\lambda \sim 0.1$cm, $\omega_p \sim 10^{15}$/s and $\tau \sim 10^{-13}$s for $n_e = 10^{20}$/cm^3. (The detail of the mean free time τ is discussed soon below.) The radiations produced in the regions deeper than the penetration depth are absorbed in dense electron gases[33]. We find that our emission mechanism of the FRBs explains the observed large amounts of their energies 10^{40}erg/s. We should note that the number density of electrons rapidly decreases to the one in the magnetosphere of the neutron star, in which the plasma frequencies are less than the intrinsc frequency $\nu_{\rm int}$.

(The surface area of the axion stars meeting the gasses is assumed to be $(10^4\mathrm{cm})^2$, although they can be larger than $(10^4\mathrm{cm})^2$ even if the axion stars are distorted[24] by tidal forces of neutron stars or black holes. Thus, actual radiation energies can be larger than the one estimated here. In this way the radiations observed are emitted from the surface of neutron stars or accretion disks. Therefore, we find that the axion star collisions with neutron stars (accretion disks) produce the radio emissions with sufficiently large amount of the energies to be consistent with observed energy fluxes of FRBs.)

In general, the radiations coming from the outside of the neutron star penetrate to the penetration depth in the surface, while the radiations produced inside by the electric currents in the penetration depth can be emitted outside. On the other hand, the radiations emitted in regions deeper than the penetration depth or skin depth are absorbed in the plasma of the regions. The results have been confirmed rigorously in our previous paper[34], in which we have calculated the opacity of the electron gases in the atmospheres of neutron stars. The coherent radiations may arrive the earth without absorption in the surroundings of the neutron stars or accretion disks just as the radio pulses from the neutron stars arrive. In our arguments the radiations are supposed to pass the regions in the magnetosphere of the neutron star with their plasma frequencies less than $\nu_{\rm int} = m_a/2\pi$ and to reach to the earth without absorption.

A comment is in order. The number density n_e of electrons used in the estimation should be regarded as the average one. When the axion star collides electron gases of the astrophysical objects, the number density of the electrons exponentially increases from the values ($\simeq 0\,\mathrm{cm}^{-3}$) in vacuum to the values ($> 10^{20}\mathrm{cm}^{-3}$) in the surfaces of the objects. In particular, the number density in atmospheres with low temperatures of neutron stars increases from $\sim 0\,\mathrm{cm}^{-3}$ in the vacuum to the one much larger than $10^{20}\mathrm{cm}^{-3}$ even at the penetration depth 0.1cm. Therefore, the value referred in the above estimation should be regarded as the average one.

The radiations emitted from the geometrically thin accretion disks are expected to be not absorbed after their emissions. Their emissions arise at the surfaces of the accretion disks near the galactic black holes where the disks are very thin. The number densities of electrons also exponentially decrease toward the outside when the gas pressure balances with the gravitational pressure in the disks. However, because the structures of the geometrically thin accretion disks are less well understand than the one of the neutron star atmospheres, we simply assume that the radiations emitted from the disks are not absorbed.

An emission mechanism in the collisions between axion stars and neutron stars has been discussed[25, 33]. The mechanism is the conversion of the axions into radiations under strong magnetic fields of the neutron stars. But the energy fluxes are not sufficiently large to be detectable when the collisions occur in extragalactic universe. This is because one axion is converted to one photon in the mechanism. Thus, the fluxes are proportional to the number of the axions in the axion star, that is, the mass M_a. Although the fluxes are not large, the radiations show the line spectrum with the frequency $m_a/2\pi$ so that we can directly determine the mass of the axions.

In the estimation of the amount of the radiation energies, we have used the mixing $\propto \alpha\, a(\vec{x},t)\vec{E}\cdot\vec{B}/f_a$ in eq(3) between the axion and the photon. Especially, the coefficient of the term derived in the vacuum has been exploited. But the coefficient has been shown[35] to be suppressed in the dense plasma by the factor $(m_a/\omega_p)^2$. The suppression is caused by the Ohm's law. That is, the Ohmic dissipation of the energy of the electric field $\vec{E}$ effectively diminishes the mixing in the dense plasma. But, our mechanism of the coherent dipole radiations works before the beginning of the suppression due to the Ohm's law. (They are emitted by oscillating electrons before the electrons interact with each other and lose their energies.) The radiations are emitted by the coherently oscillating electrons. The oscillations last until the thermal fluctuations disturb them. Such large thermal fluctuations are realized by the thermalization of the oscillating energies. In other words, the coherent radiations last the mean free time of the electrons. Therefore, our use of the mixing in the vacuum is valid for the above estimation.

The emissions of the FRBs are stopped by thermal fluctuations. Namely, the oscillation energies are thermalized so that the temperatures of the electron gases increase. Eventually, the thermal fluctuations disturb the coherent radiations. The critical temperature T_c at which the coherent emissions stop is determined by the oscillation energies $p^2/2m_e \simeq (eE_0/m_a)^2/2m_e$. The thermal energies are equal to the oscillation energies. The durations of the bursts may be approximately given by the mean free time of electrons at the temperature T_c. So we roughly estimate mean free time τ of electrons. Electrons interact with each other by the Coulomb interaction. When the cross section of the electrons is πl^2, the mean free time τ is given by $\tau = 1/(\pi l^2 n_e v)$ where the velocity v of electrons is $\sqrt{2T_c/m_e}$. The cross section πl^2 is estimated such that the distance l between electrons satisfies $\alpha/l \simeq T_c \simeq (eE_0/m_a)^2/2m_e$; Coulomb energy is equal to kinetic energy. Thus, the mean free time is given by

$$\tau(T_c) \simeq \frac{\sqrt{m_e}T_c^{3/2}}{\sqrt{2}\pi\alpha^2 n_e} \sim 10^{-7}\mathrm{s}\Big(\frac{T_c}{10^5\mathrm{eV}}\Big)^{3/2}\Big(\frac{10^{20}\mathrm{cm}^{-3}}{n_e}\Big), \tag{9}$$

where we tentatively used the number density $n_e \sim 10^{20}/\mathrm{cm}^3$ of electrons and the critical temperature $T_c = 10^5\mathrm{eV}$.

(The critical temperature T_c depends on the magnetic field B; $T_c \sim 10^5\text{eV}(eB/10^{11}\text{G})^2$.) We may consider that the mean free time of electrons is roughly equal to the intrinsic duration of the coherent radiations. This intrinsic duration is much less than the observed values. Owing to the effects of electron gases in intergalactic space or near the source of the FRBs, the observed durations (pulse widths) become much longer than the intrinsic one. In this way, we find that the observed durations $\sim$ 1ms of the FRBs are consistent with the above estimation in the axion model. (We have not taken into account the thermal effects on the number densities n_e in the above calculations. In general, the number densities n_e depend on the temperatures. Thus, the densities decrease as the temperatures increases. Then, the intrinsic dulations τ become longer.)

When the bursts begin to be emitted, initial temperatures are much lower than 10^5eV. If we consider the temperature such as 1eV$\sim 10^4$K, the mean free time is much short such as $\tau \sim 10^{-14}$s. The mean free time leads to the small conductivity $\sigma \sim 10^{14}/s$ and the large penetration depth $\lambda \sim 0.1$cm.

In addition to the coherent radio emissions, some ejecta from the accretion disks may arise in the axion star collision with the accretion disks. The observed coherent radiations are emitted from the surface. On the other hand, the coherent radiations produced deeply inside the accretion disks are absorbed inside the disks themselves. They cannot be emitted outside the disks. Because the energies of the coherent radiations are extremely large as estimated above, the gases absorbing such large amount of the energies can be ejected outside the disks. The ejecta is composed of electrons and ions. Therefore, in the collision between the axion star and the accretion disk, the gases with their energies more than the observed energies $\sim 10^{40}$erg/s are ejected from the accretion disk. The ejecta would form or power the observed persistent radio source in the FRB 121102. Obviously, the energies carried by the ejecta are restricted such that they are less than the mass of the axion star; $M_a \sim 10^{-12}M_\odot \sim 10^{43}$erg. If they go beyond the mass M_a, the axion star evaporates with its collision with the disk.

V. SPECTRAL AND TEMPORAL PROPERTIES OF FRBS

Now, we analyze the properties of FRBs, especially, the detailed properties of the FRB121102 by using the axion model. First, the spectra of the repeating FRB 121102 have been recognized to be narrowband, not broadband. The spectra are characterized with two parameters; center frequency ν_c and bandwidth $\delta\nu$. According to the axion model, the line emissions are broadened by thermal effects. Such spectra are given by

$$S(\nu) \propto \exp\Big(-\frac{(\nu-\nu_c)^2}{2(\delta\nu)^2}\Big), \tag{10}$$

with the bandwidths $\delta\nu = \nu_c\sqrt{T_c/m_e}$. We notice that the bandwidths are proportional to the center frequencies ν_c. This is a property resulted from the effects of the thermal fluctuations on the line spectra.

Such a proportionality has been observed to be roughly valid,

$$\begin{aligned}
\delta\nu &\sim 1000\text{MHz} \quad \text{for center frequencies} \quad \nu_c \sim 6\text{GHz in the ref.[13]} \\
\delta\nu &\sim 500\text{MHz} \quad \text{for center frequencies} \quad \nu_c \sim 3\text{GHz in the ref.[5]} \\
\delta\nu &\sim 300\text{MHz} \quad \text{for center frequencies} \quad \nu_c \sim 2\text{GHz in the ref.[4]} \\
\delta\nu &\sim 200\text{MHz} \quad \text{for center frequencies} \quad \nu_c \sim 1.2\text{GHz in the ref.[3]}.
\end{aligned} \tag{11}$$

Although the observations exhibit that each width $\delta\nu$ with an almost identical center frequency vary depending on each burst, the above values have been taken as typical ones. (Indeed, the variations in the widths are not large; for instance, the variations is given such that 400MHz $< \delta\nu <$ 700MHz for the center frequency $\nu_c \simeq$ 3GHz [5] whose bandwidth is referred as $\sim$ 500MHz.) The proportionality is never strict, but we can see such a tendency in the spectra. The theoretical prediction by the axion model is that the proportional constant $\sqrt{T_c/m_e} = eE_0/(\sqrt{2}m_a m_e) \propto (M_a m_a)^2 B$ depends on the strength of the magnetic field B. (It also depends on the masses M_a of the axion stars, which may take a value in a range $(10^{-12}M_\odot \sim 10^{-11}M_\odot)$.) Thus the variation in the widths $\delta\nu$ at an identical center frequency comes from the variation in the magnetic fields or the masses of the axion stars.

It is interesting that the widths $\delta\nu$ are estimated such as ,

$$\delta\nu = \nu_c\sqrt{\frac{T_c}{m_e}} = \frac{\nu_c e E_0}{\sqrt{2}m_a m_e} = 590\text{MHz}\,\frac{\nu_c}{3\text{GHz}}\,\frac{eB}{5\times10^{10}\text{G}}\Big(\frac{M_a}{2\times10^{-12}M_\odot}\Big)^2. \tag{12}$$

where we take the strength of the magnetic fields $eB \simeq 5 \times 10^{10}$G. It is remarkable that by using the almost identical strengths of the magnetic fields $B = (10^{10}\text{G} \sim 10^{11}\text{G})$ for the evaluation of the burst energies $\dot{W}$, durations $\tau(T_c)$ and bandwidths $\delta\nu$, we can obtain corresponding observed values of the FRBs.

Now, we proceed to answer why there are various center frequencies ν_c; $1\text{GHz} < \nu_{\rm c} < 7\text{GHz}$. It apparently seem that the frequency of the dipole radiations is uniquely given by $\nu_{\rm int} = m_a/2\pi$ in the axion model. We should note that the radiations of the FRB 121102 are emitted from the electron gases in the accretion disks which the axion stars collide. The disks can closely orbit a galactic black hole and then their velocities $\vec{V}$ can be relativistic. Thus, the radiations emitted from the disks are Doppler shifted. The Doppler shift is given by $\nu_c(V) = \nu_{\rm int}\Pi(V)$ with $\Pi \equiv \sqrt{1-V^2}/(1 - V\cos\theta)$ where θ denotes the angle between the direction of $\vec{V}$ and the line of sight. Therefore, the frequencies ν_c can take large values such as 6GHz when $V = |\vec{V}| \simeq 0.95$ and $\theta \simeq 0$ when $\nu_{\rm int} = m_a/2\pi \simeq 1.4\text{GHz}\big(m_a/0.6 \times 10^{-5}\text{eV}\big)$. Various velocities V of the disks give rise to the various center frequencies ν_c. This is the reason why there are bursts with various center frequencies in the repeating FRB 121102. We can predict from the discussion that the bursts with frequencies much larger than 10GHz are absent because the velocity of the disks from which such radiations are emitted, must be almost equal to light velocity. The axion star collisions with such disks might be extremely rare.

The recently observed repeating FRB 180814.J0422+75 shows the lower center frequencies $\sim$ 700 MHz than the ones the FRB 121102 shows. This implies the angle $\theta \sim \pi$ in the collision between axion stars and accretion disk associated with the FRB 180814.J0422+75.

The Doppler shifts also give rise to a temporal property pointed out in the reference [13] that durations $\tau(\nu_c)$ of bursts with higher center frequencies ν_c are shorter than those with lower center frequencies. The durations shorten owing to the Doppler effect, that is, $\tau = \tau_{\rm int}\Pi^{-1}(V)$. The duration $\tau_{\rm int}$ denotes the duration measured by observers moving with the disks. So, $\tau(\nu_c) < \tau(\nu_c')$ when $\nu_c(V) > \nu_c'(V')$, that is $V > V'$. It is obvious that the product of ν_c and duration $\tau(\nu_c)$ does not receive the Doppler effect. The feature can be seen in the Fig.7 of the reference[13]. Our argument holds under the assumption that the durations observed at the earth are proportional to the durations observed near the source of the radiations: The propagation effects on the durations do not change the result. (Actually, it has been discussed[36] that the broadened pulse widths caused by intergalactic medium effects are smaller than the intrinsic ones discussed in the paper. This is because the location of the galaxy involving the source of the FRB 121102 is near the Milky Way Galaxy, that is, its redshift is $z \simeq 0.2$.)

(It appears that the Doppler effect gives rise to larger peak flux densities $S(\nu_c)$ as the center frequencies become higher; $S(\nu_c) = (\nu_c/\nu_c')^3 S(\nu_c')$. The Doppler effect make flux densities S_0 large such as $S = S_0\Pi^3$. The effect on S is much larger than the effect on τ or ν_c. But the trend can not be observed[13] in the FRB 121102. As pointed out[13], the distribution of the peak flux densities are almost flat in the range 1GHz $\sim$ 6GHz. Probably, the flat distribution comes from the fact that both of the electron number densities n_e and the strength of magnetic fields B become smaller[22, 23] as the accretion disks closer approach the black hole, for instance, $n_e \propto r$ and $B \propto r$ where r denotes the radial coordinate measured from the center of the black hole. Then, because $\dot{W}$ are proportional to $(Bn_e)^2 \propto r^4$, the observed flux densities $S(r) \propto \dot{W}(r)$ emitted from the disks at r can be expressed by those $S(r')$ emitted from disks at r' ($r' > r$) such that $S(r) = (r/r')^4(\nu_c/\nu_c')^3 S(r')$. Note that $\nu_c(r) > \nu_c'(r')$. The factor $(r/r')^4$ would diminish the influence of the Doppler effect, i.e. $(\nu_c/\nu_c')^3$ on the peak flux densities. Thus, the distribution of the observed flux densities must be almost flat. We should make a comment that the dependences of $V(r)$ and $n_e(r)$ on r depend on each model of the accretion disks. So we can not precisely estimate the factor $(r/r')^4$.)

Non repeating FRBs are generated by the axion star collision with neutron stars, while repeating FRBs are generated by its collision with accretion disks of black holes. Both objects have strong magnetic fields. In general we expect that the magnetic fields of the neutron stars are stronger than those of the accretion disks. Stronger magnetic fields produce larger flux densities of FRBs because $\dot{W}$ in eq(7) is proportional to B^2. Actually, the flux densities of the non repeating FRBs are roughly ten times larger than those of the repeating FRB 121102. The difference may come from the difference in the magnetic fields of the astrophysical objects. Obviously, the flux densities also depend on the electron number densities n_e. ($\dot{W}$ is proportional to n_e^2.) The average number densities of electrons producing FRBs in the neutron stars might be larger than corresponding number densities of electrons in the accretion disks. Thus, we can not determine which one is the main cause leading to the difference in the flux density. Probably, both causes make a difference in flux densities of non repeating FRBs and the repeating FRB.

Furthermore, the difference in the magnetic fields gives rise to the difference in the bandwidths of FRBs. The bandwidths depend only on the magnetic fields but not on electron number density n_e; $\delta\nu$ in eq(12) is proportional to B. We expect that the bandwidths of the non repeating FRBs are much larger than those of the repeating FRB. Indeed, the bandwidths of non repeating FRBs have not yet been detected. They would be too large to be in the extent of receiver frequency ranges. They have been observed only in the frequency range 0.8GHz $\sim$ 1.6GHz. (People might think that the bursts are broadband.) The bandwidths of the non repeating FRBs would be 3 $\sim$ 5 times larger than those of the repeating FRBs. Namely, $\delta\nu$ of the non repeating FRBs may be 600MHz $\sim$ 1GHz at the center frequency 1.4GHz. The bandwidths are over the extent of the receiver frequency range. (The very recent MWA observations[21] at the frequency 200MHz have not detected non repeating FRBs, although they have been detected by simultaneous ASKAP observation at frequency 1.4GHz. It suggests that the non repeating FRBs are not broadband and their bandwidths are less than 1.2GHz.) If observations with the wide extent of the receiver frequency range (e.g. a frequency range 1GHz $\sim$ 3GHz) are performed, the bandwidths of the non repeating FRBs could be observed.

The repeating FRB 121102 takes place when the axion stars collide the accretion disk of a galactic black hole. In particular, they collide the accretion disk several times orbiting the black hole and finally they evaporate or fall into the black hole. Then, we expect that the time sequence of the bursts (collisions) gradually shortens while an axion star collides the disk several times, falling into the black hole. We can see such a trend in the recent observation[37]: After a long period of ~ 100 seconds in which there are no bursts, the bursts arise in subsequent ten seconds and show such a trend. On the other hand, the axion stars are extremely distorted or split by the tidal force of the black hole. Then, the sequence would become complex. Indeed, some of the bursts in the FRB 121102 exhibit a few peaks in their spectra[13]. That is, 2 or 3 peaks appear within a few msec. They might be caused by the splitting of the axion star. Although the complexity in the time sequence is present, we can see that the distribution[37] of the time intervals between sequent bursts is concentrated in shorter span and non vanishing even in longer span. The concentration might be caused by the axion stars falling into the black hole as they orbit.

The observations[37] also exhibit many bursts with low flux densities $\sim$ 50mJy of compared with the flux densities previously observed[13]. It suggests that the bursts with low flux densities arise from the axion stars with smaller masses than the one ($\sim 2\times10^{-12}M_\odot$) referred in the present paper. Probably, the axion stars with smaller masses might be produced by the splitting of original axion stars with masses $\sim 2\times10^{-12}M_\odot$.

It has recently been reported[6] that a new FRB 180814.J0422+75 with low frequencies 400MHz $\sim$ 800MHz has been observed. It is interesting that the spectra of all repeating bursts with such low frequencies are narrowband. Furthermore, the bandwidths of the bursts with the center frequencies $\sim$ 700MHz (450MHz) are approximately given by 90MHz (50MHz). The result is coincident with our results mentioned above; the bandwidths are proportional to the center frequencies. More interestingly, we can see the feature that pulse widths (dulations) are broader as the center frequencies are lower. The feature is identical to the one observed in FRB 121102. All of these properties of the FRB 180814.J0422+75 are caused by Doppler effects on the radiations emitted by the accretion disks of galactic black holes.

CHIME[38] has observed 13 bursts, one of which is the repeating FRB 180814.J0422+75. According to our axion model, the bursts with the maximum frequencies much less than 800MHz are necessarily repeating FRBs. At least, the bursts are emitted by the accretion disks. Similarly, the bursts with the lowest frequencies much higher than 2GHz, the bursts are repeating FRBs.

The repeating FRBs arises from the collisions between the accretion disks and the axion stars. The angle θ between the velocity $\vec{V}$ of the accretion disk hit by the axion star and the line of sight can take values $0<\theta<\pi$. When $\theta\sim0$ ($\theta\sim\pi$), the burst frequencies are higher (lower) than 2GHz (800MHz). Therefore, we predict that the bursts with low frequencies such as 600MHz are observed for FRB 121102, while the bursts with high frequencies such as 3GHz are observed for the FRB 180814.J0422+75.

VI. DISCUSSION AND SUMMARY

As we have mentioned, rotation measures of FRBs have been obtained[19, 20]. The rotation measures[20] of the FRB 121102 are very large such as $\sim 10^5$rad m^{-2}, while those of the non repeating FRBs are at most $\sim 2\times10^2$rad m^{-2}. It indicates that the environment of the FRB121102 is similar to the one of PRS J1745-2900 located near the black hole in the Milky Way galaxy, while those of the non repeating FRBs are similar to environments of ordinary pulsars in the Milky Way galaxy. These observations are consistent with the axion model; non repeating FRBs arise from neutron stars and the repeating FRBs do from accretion disks of galactic black holes.

We have analyzed spectral and temporal properties of FRBs by using the axion model. The model states that the axion star collisions with neutron stars cause non repeating FRBs, while their collisions with accretion disks of galactic black holes cause repeating FRBs. Electron gases on the surfaces of the astrophysical objects emit coherent radiations when the axion stars collide them. This is because the axion stars generate spatially homogeneous oscillating electric fields when they are under homogeneous strong magnetic fields. The electric fields make electrons coherently oscillate and emit the coherent radiations. The homogeneity should hold over the region with the volume such as $(10^4\text{cm})^2\times0.1\text{cm}\simeq10^9\text{cm}^3$, from which the coherent radiations are emitted. But, the coherent radiations stop because the thermal fluctuations owing to the thermalization of the oscillation energies disturb the coherent oscillations of the electrons. We have shown that the durations of the FRBs are much shorter than 1ms. The thermal effects make the spectra of the radiations broaden. Because the accretion disks can orbit with relativistic velocities in the vicinity of the black holes, the radiations emitted from the disks are Doppler shifted. Accordingly, the radiations with higher center frequencies (2GHz $\sim$ 8GHz) than the intrinsic frequency $m_a/2\pi \simeq 1.4\mathrm{GHz}(m_a/0.6\times 10^{-5})\mathrm{eV}$ are observed in the repeating FRB 121102. Similarly, these bursts with higher frequencies exhibit shorter durations than those of bursts with lower frequencies due to the Doppler effects.

Non repeating FRBs show larger flux densities than those of the repeating FRB 121102. It may be caused by stronger magnetic fields of neutron stars than the ones of the accretion disks. Such strong magnetic fields produce large bandwidths of non repeating FRBs so that they are over the extent of the present receiver frequency range. This is the reason why the spectra of the repeating FRBs are found to be narrowband, but the spectra of the non repeating FRBs are not.

We have discussed that in addition to the coherent radiations emitted from the surfaces of accretion disks, ejecta with the energies such as 10^{39}erg are produced in the axion star collisions with the accretion disks. They arise owing to the absorption of the coherent radiations by the disks themselves; the radiations are produced inside of the disks. In particular, these ejecta repeatedly take place in the repeating FRB 121102. The ejecta would form the observed persistent radio source or could be an energy source of the persistent radio source associated with the FRB 121102.

The axion stars are coherent states of gravitationally loosely bounded axions and their forms are easily deformed by tidal forces of neutron stars or black holes. They could be split by the tidal forces just before their collisions with the astrophysical objects. Thus, the complex structures such as 2 or 3 peaks in the spectra within a few ms would arise.

After finishing the paper, the new repeating FRB 180814.J0422+75 was found. The new repeating bursts have lower center frequencies than 1GHz contrary to those of the FRB 121102. It is remarkable that their spectral properties are coincident with our results mentioned above; narrow bandwidths $\delta\nu$ proportional to center frequencies ν_c, their proportional constant $\delta\nu/\nu_c \sim (0.1 \sim 0.2)$ roughly coincident with the one of the FRB 121102 and pulse widths τ proportional to ν_c^{-1}.

We would like to add a new prediction of the axion mass which can be derived by the recent observation[39] of the FRB121102. The observation shows the presence of the bursts with the center frequency $\simeq 1.4$GHz with narrow bandwidths less than 100MHz and with low fluences ~ 0.03mJy. The bursts are thought to be emitted in the accretion disks with relatively low velocity. This is because the narrow bandwidths and the low fluences imply that they are produced in the gases with relatively weak magnetic fields. Those magnetic fields are located in the accretion disks relatively far away from the galactic black hole. Because the source of the bursts is located at $z \simeq 0.193$, the intrinsic frequency $m_a/2\pi$ of the bursts is nearly equal to 1.67GHz; the axion mass $\simeq 7.16\times 10^{-6}$eV.

According to the results obtained in the paper, we conclude that the axion model for the FRBs well explains most of all features of non repeating and repeating FRBs.

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