Explanation of Detailed Spectral Properties of FRBs by Axion Star Model

Aiichi Iwazaki
Nishogakusha University,
6-16 Sanbantyo Chiyoda Tokyo 102-8336, Japan.
(Dated: Oct. 10, 2018)

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 thermalization 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 $\nu_c$: $\delta\nu \propto \nu_c$. 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~7GHz) in repeating FRB121102. 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, peak flux densities of non repeating FRBs are larger than those of repeating FRB121102. 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. We predict that the recently discovered FRB180725A is a new repeating FRB.

PACS numbers: 14.80.Va, 98.70.-f, 98.70.Dk

Axion, Fast Radio Burst, Accretion disk

I. INTRODUCTION

Since a Fast Radio Burst (FRB) has been originally reported[1], more than 30 FRBs have been observed. Among them, only a FRB121102 emit bursts repeatedly[2,3] and so is named as repeating FRB. The detailed follow up observations of the FRB121102 have been performed. As a consequence, we have obtained detailed spectral and temporal properties of the FRB121102 in a wide frequency range 1GHz~8GHz. On the other hand, the other ones 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~1.6GHz. Although observations[6] at low frequencies 145MHz, 182MHz and 350MHz have been performed, any FRBs have not been detected. These fundamental properties can be explained by many models[7] 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[8,9] have shown that the FRB121102 is originated in a dwarf galaxy with redshift $z \simeq 0.19$. The galaxy is conjectured to be an AGN. The bursts of the FRB121102 have been observed[4,5,11,12] with multiple bands 1.2GHz~1.5GHz, 1.7GHz~2.3GHz, 2.5GHz~3.5GHz, 4.5GHz~5GHz and 4GHz~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[13,14] 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[15,16], which have been confirmed by simultaneous observations of radio frequencies. 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 FRB121102 indicate that the bursts are really narrowband just as molecular line emissions. Our axion model predicts that the feature is common to non repeating FRBs; 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 $\nu_c$; $\delta \nu \propto \nu_c$. For instance, we can see bandwidths roughly given by $\sim 500\text{MHz}$ at the center frequencies $\sim 3\text{GHz}$ and similarly $\sim 1\text{GHz}$ at the frequencies $\sim 6\text{GHz}$. It seems that the proportionality holds even for the bursts with the frequencies $\sim 2\text{GHz}$ (their bandwidths $\sim 300\text{MHz}$) and $1.3\text{GHz}$ (bandwidths $\sim 200\text{MHz}$).

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[11] that in the FRB121102 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 $\nu_c$.

The follow up observations clarify the presence of a persistent radio source spatially coincident with the bursting source of the FRB121102. 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 magnetar model for the FRB121102.

Rotation measures of FRBs have also been obtained[17, 18]. The radiations of the FRB121102 are 100% linearly polarized. It is notable that the rotation measures of the FRB121102 are very large such as $\sim 10^3\text{rad m}^{-2}$, while those of the non repeating FRBs are at most $\sim 2 \times 10^2\text{rad m}^{-2}$. 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 FRB121102 lead to a conjecture that the source of the FRB121102 might be a newly born magnetar or would be associated with AGN.

These spectral and temporal properties of the repeating FRB121102 are clue to find sources of the fast radio bursts. In the paper we explain all of the properties by using the axion model[13, 14]: axion star collides with neutron stars (source of non repeating FRBs) and with accretion disks of galactic black holes (source of repeating FRBs like FRB121102). 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 ($< 200\text{MHz}$) or high frequencies ($> 3\text{GHz}$). 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 those of the repeating FRB. Additionally, it may cause too large bandwidths ($> 1\text{GHz}$) of non repeating FRBs to be observable; they are over the extent of the receiver frequency ranges. Indeed, their bandwidths have not been detected. (Very recent observation[19] exhibits that spectra of non repeating FRBs have no components with low frequencies. It suggests that the bursts are not broadband like the repeating FRB121102 and their bandwidths are larger than those of the repeating FRBs with frequencies $\sim 1.4\text{GHz}$.) 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 $\sim 10^{10}\text{G}$. Actually, there is a model[20, 21] 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 with 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 FRB121102. The ejecta could be an energy source of the observed persistent radio source in the galaxy associated with the FRB121102.

The axion stars are coherent states of axions. We present approximate solutions of gravitationally loosely bound states of the axions in the section[11]. Although they are spherical, actual forms of the axion stars are extremely distorted[22] 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[14]. This is because the tidal forces do not change the masses of the axion stars. The parameters characterizing the axion stars are almost
fixed by their masses. These parameters are used for the evaluation of the emission properties of FRBs.

II. COHERENT DIPOLE RADIATIONS

FRBs are coherent radiations because their energy fluxes are extremely large \( \sim 10^{49} \text{erg/s} \) and the sizes of their sources are small \( \sim 1 \text{ms} \times 10^{16} \text{cm/s} = 10^7 \text{cm} \). 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 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 is very simple. First, we notice that electrons can coherently emit radiations when they are imposed by spatially homogeneous oscillating electric field \( \vec{E}(t) = E_0 \cos(m_at) \). ( 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 \( \vec{p}(t) = eE_0 \sin(m_at)/m_a + \vec{p}(t = 0) \). 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.

In general, the coherent oscillations are disturbed by thermal fluctuations. The momentum of the electron at temperature \( T \) is given by \( \vec{p}(t) + \vec{p}_{\text{thermal}} \) with \( \vec{p}_{\text{thermal}}/2m_e = T \) 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 gas 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 \( T_c \approx \vec{p}(t)^2/2m_e \approx (eE_0/m_a)^2/2m_e \). 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 Nambu-Goldstone boson\(^\text{[23]}\) 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 \( G_{\mu,\nu}G^{\mu,\nu} \) is absent in QCD Lagrangian where \( G_{\mu,\nu} \) ( \( G^{\mu,\nu} \) ) denotes ( dual ) fields strength of gluons. ( If the exact chiral symmetry is present, the term can be made to vanish. ) 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 as oscillations\(^\text{[24, 25]}\); the axion stars are gravitationally bounded states of axions. In the early Universe, axion miniclusters\(^\text{[26]}\) 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\(^\text{[25, 27]}\) 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\(^\text{[28]}\) are given by

\[
a = a_0 f_a \exp(-r/R_a) \cos(m_a t) \quad \text{with} \quad a_0 = 0.8 \times 10^{-7} \left( \frac{M_a}{2 \times 10^{-12} M_\odot} \right)^2 \left( \frac{m_a}{0.6 \times 10^{-5} \text{eV}} \right)^3
\]

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

\[
R_a = \frac{1}{G M_a m_a^2} \approx 360 \text{km} \left( \frac{0.6 \times 10^{-5} \text{eV}}{m_a} \right)^2 2 \times 10^{-12} M_\odot
\]
where $G$ denotes the gravitational constant. The decay constant $f_a$ is related with the mass $m_a$: $m_a \approx 6 \times 10^{-6} \text{eV} \times (10^{12} \text{GeV}/f_a)$. There are two unknown parameters $m_a$ and $M_a$ (or $R_a$). The mass $M_a$ ($\text{radius } R_a$) of the axion star was obtained\cite{13,22} by comparing the collision rate between neutron stars and axion stars in a galaxy with the event rate of FRBs $\sim 10^{-1}$ per year in a galaxy. 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 $\sim 0.6 \times 10^{-5} \text{eV}$ so as for the intrinsic frequency $\nu_{\text{in}}$ of the non repeating FRBs to be given by $m_a/2\pi \approx 1.4 \text{GHz}$. The value is in a window allowed in axion searches. ( The observed frequencies $\nu$ receive effects of cosmological expansions such that $\nu = \nu_{\text{in}}/(1+z)$ 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 even if the volume becomes 10 times larger, the value $a/f_a$ of the axion mass $m_a$ 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\cite{22}. It implies that the deformed axion stars can be treated classically just as classical electromagnetic waves.

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. 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 $M_a = \int d^3x ((\partial_\alpha a)^2 + (\partial_\alpha \bar{a})^2 + (m_a a)^2)/2 \sim (m_a a)^2 \times \text{“volume of the axion star”}$. 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 $a_0$ 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,

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

with the fine structure constant $\alpha \approx 1/137$, 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;

$$\vec{\partial} \cdot \vec{E} + \frac{\alpha \vec{\partial} \cdot (a(\vec{x}, t) \vec{B})}{f_a \pi} = 0 \ , \ \vec{\partial} \times (\vec{B} + \frac{\alpha \vec{\partial} \cdot (a(\vec{x}, t) \vec{E})}{f_a \pi}) - \partial_t (\vec{E} + \frac{\alpha \vec{\partial} \cdot (a(\vec{x}, t) \vec{B})}{f_a \pi}) = 0,$n(4) \n
From the equations, we approximately obtain the electric field $\vec{E}$ generated on the axion stars under the background homogeneous magnetic field $\vec{B}$,

$$\vec{E}_a(r, t) = -\frac{a(\vec{x}, t) \vec{B}}{f_a \pi} = -\frac{a_0 \exp(-r/R_a) \cos(m_a t) \vec{B} (\vec{r})}{\pi} \approx 1.3 \times 10^{-1} \text{eV}^2 (\sim 0.7 \times 10^4 \text{eV/cm}) \cos(m_a t) \left(\frac{M_a}{2 \times 10^{-12} M_\odot}\right)^2 \left(\frac{m_a}{0.6 \times 10^{-5} \text{eV}}\right)^3 \frac{B}{10^{10} \text{G}} \vec{B}.$$

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

This is the electric field discussed in the previous section. It oscillates with the frequency $m_a/2\pi$ 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 to the inside of the disks, the electric fields point to 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 to the outside of the neutron stars but not necessarily point to 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,

$$T_c = \left(\frac{e E_0}{m_a}\right)^2 \frac{1}{2 m_e} \approx 0.5 \times 10^3 \text{eV} \left(\frac{e B}{10^{10} \text{G}}\right)^2 \left(\frac{M_a}{2 \times 10^{-12} M_\odot}\right)^4 \left(\frac{m_a}{0.6 \times 10^{-5} \text{eV}}\right)^4.$$


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

We should mention that the electrons possess thermal energies (e.g. \( T_c \approx 10^8 \text{eV} \)), while they are trapped by the strong magnetic fields \( B \). 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 (\(< 1 \text{ms}\) ), the clump of the electrons may flow outside the surface. The transverse cross section of the clump is given by, for instance, \( \sim (10^4 \text{cm})^2 \), while its longitudinal length is less than \( \sqrt{2T_c/m_e} \times 1 \text{ms} \approx 3 \times 10^4 \text{cm} \sqrt{T_c/10^8 \text{eV}} \). The transverse cross sections are those of the axion stars meeting the surfaces of the neutron stars or accretion disks, while the longitudinal length is less than the one the electrons can proceed within the durations of FRBs. The observed radiations are produced in the regions near the surfaces.

More importantly, ejecta with large energies are produced by the axion star collision with the accretion disk. We note that coherent radiations are emitted even in deep inside of the neutron stars or the accretion disks. They are absorbed inside the astrophysical objects. The gases absorbing the radiations can be ejected outside the astrophysical objects, in particular, geometrically thin accretion disks. This is because the energies of the radiations are extremely large and deposited with a very short time less than 1 ms. (We should note that the radiations point to the outside of the disks.) These ejecta would form a persistent radio source or could power the persistent source observed in the vicinity of the FRB121102. 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 \( 10^{40} \text{erg/s} \) when the axion stars collide neutron stars or accretion disks with strong magnetic fields. Because each electron emits the energy \( \sim e^2p^2/3m_e^2 = e^4E_0^2/3m_e^2 \) in the oscillating electric field \( \vec{E} = E_0 \cos(m_e t) \) in eq. (5), the electrons in the volume \( (2\pi/m_a)^3 \approx (20 \text{cm})^3 \) can emit coherent radiations with the energies per unit time,

\[
W \approx 10^{33} \text{erg/s} \left( \frac{n_e}{10^{18} \text{cm}^{-3}} \right)^2 \left( \frac{M_a}{2 \times 10^{-12} M_\odot} \right)^4 \left( \frac{B}{10^{10} \text{G}} \right)^2,
\]

where \( n_e \) denotes electron number density assumed to be large such as \( 10^{18} \text{cm}^{-3} \). Thus, the radiation energies \( 10^{33} \text{erg/s} \times (10^8/10^5)^2 \approx 10^{41} \text{erg/s} \) emitted from a volume such as \( (2 \times 10^3 \text{cm})^2 (2\pi/m_a) \approx 10^4 (20 \text{cm})^3 \sim 10^8 \text{cm}^3 \) are larger than the observed values \( 10^{40} \text{erg/s} \). (When the axion stars collide with electron gases, the surfaces of the axion stars meeting the gases can be much larger than \( (2 \times 10^4 \text{cm})^2 \) even if they are distorted by tidal forces of neutron stars or black holes. Thus, actual radiation energies are much larger than the one in eq. (7). Radiations emitted from regions deeper than the surface with depth \( 2\pi/m_a \) may be absorbed by electron gases themselves. They are not emitted into the Universe.) 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.

We would like to mention about the number density \( n_e \) of electrons. The value 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 gradually increase from the values (\( \sim 0 \text{ cm}^{-3} \)) in vacuum to the values (\( > 10^{18} \text{cm}^{-3} \)) in deep inside of the objects. In particular, the number density in atmospheres of neutron stars increases from \( \sim 0 \text{ cm}^{-3} \) in the vacuum to the one much larger than \( 10^{18} \text{cm}^{-3} \) at the depth \( 2\pi/m_a \approx 20 \text{ cm} \). Therefore, the value referred in the above estimation should be regarded as the average one.

Such emissions 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 \( p^2/2m_e \approx (eE_0/m_a)^2/2m_e \). 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 \( \tau \) of electrons. Electrons interact with each other by the Coulomb interaction. When the cross section of the electrons is \( \pi \tau^2 \), the mean free time \( \tau \) is given by \( \tau = 1/(\pi \tau^2 n_e v) \) where the velocity \( v \) of electrons is \( \sqrt{2T_c/m_e} \). The cross section \( \pi \tau^2 \) is estimated such that the distance \( l \) between electrons satisfies \( \alpha/l \approx T_c \approx (eE_0/m_a)^2/2m_e \); Coulomb energy is equal to kinetic energy. Thus, the mean free time is given by

\[
\tau(T_c) \approx \frac{\sqrt{m_e T_c^{3/2}}}{\sqrt{2\pi a^2 n_e}} \approx 10^{-5} \left( \frac{T_c}{10^8 \text{eV}} \right)^{3/2} \left( \frac{10^{18} \text{cm}^{-3}}{n_e} \right),
\]
where we tentatively used the number density $n_e \sim 10^{18}/\text{cm}^3$ of electrons and the critical temperature $T_e = 10^5\text{eV}$. (The critical temperature $T_e$ depends on the magnetic field $B$; $T_e \sim 10^5\text{eV}(eB/10^{11}\text{G})^2$.) 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. The propagations of the radiations receive the effects of electron gases in intergalactic space or near the source of the FRBs so that the observed durations become much longer than the intrinsic one. In this way, we find that the observed durations of the FRBs are consistent with the estimation in the axion model.

In addition to the coherent radio emissions, some ejecta from the accretion disks may arise in the axion star collision with the accretion disks. Here we estimate the energies of such ejecta. The observed coherent radiations are emitted from the surface with a volume, for instance, $(2 \times 10^3\text{cm})^2 \times 20\text{cm} \sim 10^8\text{cm}^3$. On the other hand, the coherent radiations produced deeply inside the accretion disks are absorbed inside the disks. They can not be emitted outside the disks. The energies of the coherent radiations are extremely large as estimated above. So, the gases absorbing such large amount of the energies can be ejected outside the disks. The coherent emissions last for the period $\tau \sim 10^{-5}\text{s}$ in each region with the depth $2\pi/m_a \simeq 20\text{cm}$. Thus, the energies of the ejecta absorbing the radiation energies are given by $10^{41}(\text{erg/s}) \times 10^{-5}\text{s} \times (10^5\text{cm}/20\text{cm})(h/10^5\text{cm}) \sim 10^{49}\text{erg}(h/10^5\text{cm})$ where we assume that the thickness of the disks are $h$. The ejecta carrying the energies are composed of electrons and ions. As we mentioned above, the actual energies are much larger than the energy $10^{49}\text{erg}$. Therefore, in a collision between an axion star and accretion disk, the gases with their energies $10^{49}\text{erg}$ are ejected from the accretion disk. The ejecta would form or power the observed persistent radio source in the FRB121102.

In the discussion, we assume appropriate parameters such as the surface area $(2 \times 10^3\text{cm})^2$ of the axion star meeting the accretion disk. Correct values of the parameters are not known. But, obviously, the energies carried by the ejecta are restricted such that they are less than the mass of the axion star; $M_a \sim 10^{-12}\text{M}_\odot \sim 10^{43}\text{erg}$. 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 FRB121102 have been recognized to be narrowband, not broadband. The spectra are characterized with two parameters; center frequency $\nu_c$ and bandwidth $\delta\nu$. According to the axion model, the line emissions are broadened by thermal effects. Such spectra are given by

$$S(\nu) \propto \exp\left( -\frac{(\nu - \nu_c)^2}{2(\delta\nu)^2} \right),$$

with the bandwidths $\delta\nu = \nu_c\sqrt{T_c/m_e}$. We notice that the bandwidths are proportional to the center frequencies $\nu_c$. 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{align*}
\delta\nu &\sim 1000\text{MHz} \quad \text{for center frequencies } \nu_c \sim 6\text{GHz in the ref.\[1\]} \\
\delta\nu &\sim 500\text{MHz} \quad \text{for center frequencies } \nu_c \sim 3\text{GHz in the ref.\[5\]} \\
\delta\nu &\sim 300\text{MHz} \quad \text{for center frequencies } \nu_c \sim 2\text{GHz in the ref.\[4\]} \\
\delta\nu &\sim 200\text{MHz} \quad \text{for center frequencies } \nu_c \sim 1.2\text{GHz in the ref.\[3\].}
\end{align*}$$

(10)

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 $400\text{MHz} < \delta\nu < 700\text{MHz}$ for the center frequency $\nu_c \sim 3\text{GHz}$ whose bandwidth is referred as $\sim 500\text{MHz}$. ) 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 $\sqrt{T_c/m_e} = eE_0/(\sqrt{2m_am_e}) \propto (M_am_a)^2B$ 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 $(10^{-12}\text{M}_\odot \sim 10^{-11}\text{M}_\odot)$.) 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,

$$\delta\nu = \nu_c\sqrt{\frac{T_c}{m_e}} = \frac{\nu_c eE_0}{\sqrt{2m_am_e}} = \frac{590\text{MHz}}{3\text{GHz}} \frac{eB}{5 \times 10^{10}\text{G}} \left(\frac{M_a}{2 \times 10^{-12}\text{M}_\odot}\right)^2.$$  

(11)
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 $B = (10^{10}$G $\sim 10^{11}$G) for the evaluation of the burst energies $\dot{W}$, durations $\tau(T_e)$ and bandwidths $\delta \nu$, we can obtain corresponding observed values of the FRBs.

Now, we proceed to answer why there are various center frequencies $\nu_c$: $1$GHz $< \nu_c < 7$GHz. It apparently seem that the frequency of the dipole radiations is uniquely given by $\nu_{\text{int}} = m_a/2\pi$ in the axion model. We should note that the radiations of the FRB121102 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 $\dot{V}$ can be relativistic. Thus, the radiations emitted from the disks are Doppler shifted. The Doppler shift is given by $\nu_c(V) = \nu_{\text{int}}\Pi(V)$ with $\Pi = \sqrt{1 - V^2/(1 - V \cos \theta)}$ where $\theta$ denotes an angle between the direction of $\dot{V}$ and the line of sight. Therefore, the frequencies $\nu_c$ can take large values such as $6$GHz when $V = |\dot{V}| \simeq 0.95$ and $\theta \simeq 0$ when $\nu_{\text{int}} = m_a/2\pi \simeq 1.4$GHz ($m_a/0.6 \times 10^{-5}$eV). Various velocities $V$ of the disks give rise to the various center frequencies $\nu_c$. This is the reason why there are bursts with various center frequencies in the repeating FRB121102. We can predict from the discussion that the bursts with frequencies much larger than $10$GHz 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 Doppler shifts also give rise to a temporal property pointed out in the reference 11 that durations $\tau(\nu_c)$ of bursts with higher center frequencies $\nu_c$ are shorter than those with lower center frequencies. The durations shorten owing to the Doppler effect, that is, $\tau = \tau_{\text{int}}\Pi^{-1}(V)$. The duration $\tau_{\text{int}}$ 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 $\nu_c$ and duration $\tau(\nu_c)$ does not receive the Doppler effect. The feature can be seen in the Fig.7 of the reference 11. 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.

( It appears that the Doppler effect gives rise to larger peak flux densities $S(\nu_c)$ as the center frequencies become higher: $S(\nu_c) = (\nu_c/\nu_c')^3S(\nu_c')$. The Doppler effect make flux densities $\dot{S}_0$ large such as $S = \dot{S}_0\Pi^4$. The effect on $S$ is much larger than the effect on $\tau$ or $\nu_c$. But the trend can not be observed in the FRB121102. As pointed out 11, the distribution of the peak flux densities are almost flat in the range $1$GHz $\sim 6$GHz. 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 20 21 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 $S(r') = (r/r')^4S(\nu_c)$.

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 FRB121102. 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(11) 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 detected. They would be too large to be in the extent of receiver frequency ranges. They have been observed only in the frequency range $0.8$GHz $\sim 1.6$GHz. ( 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 $600$MHz $\sim 1$GHz at the center frequency $1.4$GHz. The bandwidths are over the extent of the receiver frequency range. ( The very recent MWA observations 19 at the frequency $200$MHz have not detected non repeating FRBs, although they have been detected by simultaneous ASKAP observation at frequency $1.4$GHz. It suggests that the non repeating FRBs are not broadband and their bandwidths are less than $1.2$GHz. ) If observations with the wide extent of the receiver frequency range ( e.g. a frequency range $1$GHz $\sim 3$GHz ) are performed, the bandwidths of the non repeating FRBs could be observed.
It has recently been reported[31] that the FRBs with low frequencies 400MHz $\sim$ 600MHz have been observed. The report exhibits that the spectrum is narrowband, although calibration for data is needed to confirm the narrow band. The data shows that the center frequency is 600MHz and the bandwidth is approximately given by 100MHz. (The bandwidth 100MHz is the one expected from the formula in eq(10) in the axion model.) The report also shows detections of additional bursts with frequency $\sim$ 400MHz within a day after the FRB180727A. According to the axion model, we predict that the FRB180727A is a new repeating FRB. In contrast with the FRB121102, the velocity of the accretion disk which produces the FRB180727A is inversely directed to the line of sight, i.e. $\theta \sim \pi$. Thus, owing to the Doppler effect the observed frequencies become low such as 400MHz $\sim$ 600MHz.

The repeating FRB121102 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[32]: After a long period of $\sim$ 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 FRB121102 exhibit a few peaks in their spectra[11]. 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[32] 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[32] also exhibit many bursts with low flux densities $\sim$ 50mJy of compared with the flux densities previously observed[11]. It suggests that the bursts with low flux densities arise from the axion stars with smaller masses than the one ($\sim 2 \times 10^{-12} M_\odot$) referred in the present paper. Probably, the axion stars with smaller masses might be produced by the splitting of original axion stars with masses $\sim 2 \times 10^{-12} M_\odot$.

VI. DISCUSSION AND SUMMARY

As we have mentioned, rotation measures of FRBs have been obtained[17, 18]. The rotation measures of the FRB121102 are very large such as $\sim 10^3$ 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 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 $(2 \times 10^3 \text{ cm})^3 (2\pi/m_a) \simeq 10^4 (20 \text{ cm})^3$, 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. 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 $m_a/2\pi \simeq 1.4\text{GHz} (m_a/0.6 \times 10^{-5}) \text{eV}$ are observed in the repeating FRB121102. Similarly, these bursts with higher frequencies exhibit shorter durations than those of bursts with lower frequencies.

Non repeating FRBs show larger flux densities than those of the repeating FRB121102. It may be caused by stronger magnetic fields of neutron stars than the ones of the accretion disks. Probably, such strong magnetic fields produce large bandwidths of non repeating FRBs so that they are over the extent of the present receiver frequency range.

We have discussed that in addition to coherent radiations, ejecta with each energy such as $10^{39}$erg or larger are produced in the axion star collisions with accretion disks. In particular, these ejecta repeatedly take place in the repeating FRB121102. The ejecta would form the observed persistent radio source or could be an energy source of the persistent radio source associated with the FRB121102.

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. Then, the complex structures such as 2 or 3 peaks in the spectra may appear within a few
We conclude that the axion model for FRBs well explain most of all features of non repeating and repeating FRBs observed.

The author expresses thanks to members of KEK for useful comments and discussions.

[1] D. R. Lorimer, M. Bailes, M. A. McLaughlin, D. J. Narkevic, F. Crawford, Science, 318 (2007) 777.
[2] L. G. Spitler, J. M. Cordes, J.W.T. Hessels, et al., ApJ, 790 (2014) 101.
[3] L.G. Spitler, P. Scholz, J.W.T. Hessels, et al. Nature, 531 (2016) 202.
[4] P. Scholz, L.G. Spitler, J.W.T. Hessels, et al. arXiv:1603.08880
[5] C.J. Law, et al. arXiv:1705.07553
[6] A. Karastergiou, et al. Mon.Not.Roy.Astron.Soc. 452 (2015) no.2, 1254.
A. Rowlinson, et al. Mon.Not.Roy.Astron.Soc. 458 (2016) no.4, 3506.
P. Chawla, et al. Astrophys.J. 844 (2017) no.2, 140.
[7] see the references, J. I. Katz, Prog.Part.Nucl.Phys. 103 (2018) 1.
[8] S. Chatterjee, et al. Nature, 541 (2017) 58.
[9] B. Morcote, et al. Astrophys.J. 834 (2017) no.2, L8.
[10] S.P. Tendulkar, et al. Astrophys.J. 834 (2017) no.2, L7.
[11] V. Gajjar, et al. arXiv:1804.04101
[12] L. G. Spitler, et al. arXiv:1807.03722
[13] A. Iwazaki, Phys.Rev. D91 (2015) no.2, 023008.
[14] A. Iwazaki, arXiv:1707.04827
[15] K. Hardy, et al. Mon.Not.Roy.Astron.Soc. 472 (2017) no.3, 2800.
[16] P. Scholz, et al. Astrophys.J. 846 (2017) no.1, 80.
[17] K. Masui, et al. Nature 528 (2015) 523.
[18] D. Michilli, et al. Nature 553 (2018) 182.
[19] M. Sokolowski, et al. arXiv:1810.02355.
[20] M.C. Begelman and J. Silk, Mon. Not. Roy. Astron. Soc. 464 (2017) no.2, 2311.
[21] M. A. Abramowicz, Living Reviews in Relativity, 16 (2013) 1.
[22] A. Iwazaki, arXiv:1512.06245
[23] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38 (1977) 1440.
S. Weinberg, Phys. Rev. Lett. 40 (1978) 223.
P. Wilczek, Phys. Rev. Lett. 40 (1978) 279.
[24] E. Seidel and W.M. Suen, Phys. Rev. Lett. 72 (1994) 2516.
[25] M. Alcubierre, R. Becerril, F. S. Guzman, T. Matos, D. Nunez and L. A. Urena-Lopez, Class.Quant.Grav. 20 (2003) 2883.
[26] E. W. Kolb and I. I. Tkachev, Phys. Rev. Lett. 71 (1993) 3051; Astrophys. J. 460 (1996) L25.
[27] F. S. Guzman and L. A. Urena-Lopez, Astrophys.J. 645 (2006) 814.
[28] A. Iwazaki, Phys. Lett. B451 (1999) 123.
[29] J. Eby, M. Leembruggen, J. Leeney, P. Suranyi and L.C.R. Wijewardhana, JHEP 1704 (2017) 099.
[30] M. S. Pshirkov, Int.J.Mod.Phys. D26, no.07 (2017) 1750068.
[31] Boyle, et al., ATel 11901.
[32] Y. G. Zhang, et al. arXiv:1809.03043