Ultra High Energy Cosmic Rays and Gamma Ray Bursts
from Axion Stars

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Abstract

We propose a model in which ultra high energy cosmic rays and gamma ray bursts are produced by collisions between neutron stars and axion stars. The acceleration of such a cosmic ray is made by the electric field, \( \sim 10^{15} \left( B/10^{12} \, \text{G} \right) \, \text{eV cm}^{-1} \), which is induced in an axion star by relatively strong magnetic field \( B > 10^{12} \, \text{G} \) of a neutron star. On the other hand, similar collisions generate gamma ray bursts when magnetic field is relatively small, e.g. \( \leq 10^{10} \, \text{G} \). Assuming that the axion mass is \( \sim 10^{-9} \, \text{eV} \), we can explain huge energies of the gamma ray bursts \( \sim 10^{54} \, \text{erg} \) as well as the ultra high energies of the cosmic rays \( \sim 10^{20} \, \text{eV} \). We estimate rate of energy release in the collisions and we find that the rate roughly agrees with observations. In addition, we show that these axion stars are plausible candidates for MACHOs. Since the axion star induces oscillating electric current under the magnetic field, observable monochromatic radiations are emitted.

14.80.Mz, 95.30.+d, 98.80.Cq, 98.70.Rz, 97.60.Jd, 05.30.Jp, 98.70.Sa, 11.27.+d
I. INTRODUCTION

The origin of ultra high energy cosmic rays (UHECRs) is one of the most mysterious puzzles in astrophysics [1]. UHECRs with energies $\sim 10^{20}$ eV cannot travel in distance more than 50 Mpc owing to the interactions between UHECRs and the cosmic background radiations [2]. Observations, however, show that there are no visible candidates for the generators of such UHECRs in the arrival directions of UHECRs. There are several models of generators for UHECRs, but none of them give satisfactory explanations. They are divided into two categories [3]. One is conventionally astrophysical models, and the other one is particle physical models. It is explained in astrophysical models that the generator could be an object such as neutron star, active galactic nuclei or the same astrophysical object as generators of gamma ray bursts. It is explained in particle physical models that UHECRs could be caused by hypothetical objects such as cosmic string [4], magnetic monopole [5], super heavy relic particles decaying today [6], etc. The astrophysical models have a difficulty that cosmic rays cannot be accelerated to such high energies. On the other hand, the particle physical model has difficulties concerning to production rate of UHECRs and a large number of theoretical assumptions on hypothetical objects.

The origin of gamma ray bursts (GRBs) is also one of the most mysterious puzzles in astrophysics [7]. Some of their energies reach $\sim 10^{54}$ erg in the case of spherical emission of the burst. It is very difficult to find a model explaining such a huge energy. There are, however, several models proposed. They are also divided into two categories, astrophysical one and particle physical one. Since conventional astrophysical explanation are optimistically believed to have no serious problems, particle physical one is not urgently needed so that no such serious model is pursued. Conventionally, astrophysicists consider that the generator could be merger of neutron star-neutron star, neutron star-black hole or the collapsar (collapse of extremely massive star), etc. Recently, there are a number of growing evidences supporting that GRBs with long duration are caused by the collapse of extremely massive star. These models are optimistically believed to explain the properties of GRBs such as amount of energies released, baryon contamination of eject, afterglow spectrum, etc. But owing to difficulties in the treatment of MHD involving neutrinos and unknown properties in the fluid of nucleons, there is no successful model among them. In particular, the problem of the baryon contamination seems difficult to be solved in conventional astrophysical models. On the other hand, in some particle physical models, axions or other unknown weakly interacting particles are used to overcome the baryon contamination problem based on the conventional astrophysical engines. Moreover, in other particle physical models, one claims that the engine is collapse of mirror star [8], cosmic string [9] or collision between axion star and neutron star [10]. The engine in these model is associated with dark matter; mirror matter, cosmic string or axion.

Among these candidates for dark matter, the axion [11–13] is the most plausible one. Probably, some of axions may form boson stars (axion stars) in the present Universe by gravitational cooling [14] or gravitational collapse of axion clumps formed at the period of QCD phase transition [15]. In this paper we explain a generation mechanism [10] of UHECRs and GRBs, and discuss their production rates. Our mechanism for both phenomena is collision between axion stars and neutron star. Different strength of the magnetic field at the surface of the neutron star yields these different phenomena, i.e. UHECR and GRB.
Furthermore, the axion stars can be plausible candidates for gravitational microlenses (MACHO [16]) with an appropriate choice of the axion mass; the choice is taken in our model for explaining huge energies $\sim 10^{54}$ erg in GRBs and extremely high energies $\sim 10^{20}$ eV in UHECRs. It is intriguing that the masses of the axion stars become those of the candidates for MACHOs with this choice of the axion mass. We also show that the collisions cause emission of observable monochromatic radiations from the axion stars [17]. We can check the validity of our model by detecting the radiations.

We have previously proposed [10] a possible generation mechanism of gamma ray burst (GRB). According to the mechanism the collision between axion star and neutron star generates a gamma ray burst; the axion star dissipates its mass energy [14,18] very rapidly under the strong magnetic field of the neutron star. Thus, the energy released in the collision is given by the mass $M_a$ of the axion star. Typically, $M_a \sim 10^{-5} M_\odot (10^{-5} \text{eV}/m_a)$ where $m_a$ ($M_\odot$) denotes the axion mass (solar mass). In the previous analysis we have taken the mass, $m_a \sim 10^{-5}$ eV, as suggested observationally in standard invisible axion models. The mass of axion star, $M_a \sim 10^{59}$ erg, corresponding to this choice, however, is not enough to explain a huge energy $\sim 10^{54}$ erg observed in GRB980123 even if moderate jet is assumed in the GRB: If the solid angle of the jet is given by $\Omega$, the energy released in the GRB is about $10^{54} \Omega/4\pi$ erg.

In the present paper, we assume that the axion mass is given by $m_a \simeq 10^{-9}$ eV, although the choice is not conventional [12,19]. Then, we can explain that the energies of GRBs can reach the huge energies $\sim 10^{54}$ erg. We can also show [10] that cosmic rays are accelerated to the energies $\sim 10^{20}$ eV.

The essence of both phenomena is that a strong electric field $\sim 10^{15} (B/10^{12} \text{G})$ eV cm$^{-1}$ is induced in the axion star when it is located under magnetic field $B$ of a neutron star. This electric field can accelerate charged particles to the huge energies $\sim 10^{20}$ eV in the case of $B > 10^{12}$ G, although such a strong electric field is unstable against electron positron pair productions. On the other hand, weaker and more stable electric field dissipates its energy in magnetized conducting medium of neutron star. In particular, in the case of neutron stars with relatively weak magnetic field $\leq 10^{10}$ G, the axion star collides directly with them and its whole energy is dissipated very rapidly in their outer crust owing to the energy dissipation of the electric field. This rapid energy dissipation produces jet of baryons, which leads to emission of GBRs. In the case of strong magnetic field $> 10^{12}$ G, however, the axion star evaporates before colliding directly with the neutron star; the evaporation occurs owing to the instability of such a strong electric field against electron-positron pairs creation [20]. Therefore, the axion star decays into electron positron pairs which are accelerated to the energies $\sim 10^{20}$ eV by the electric field during its decay. In both cases the energies released are given by the mass of the axion star. Since the mass of the axion star is given by $\sim 10^{-1} M_\odot \simeq 10^{53}$ erg with the assumption of $m_a \simeq 10^{-9}$ eV, the energy $\sim 10^{54}$ erg observed in some GRBs can be explained by assuming a moderate jet of the GRBs. Thus the collisions between the axion stars and the neutron stars are possible sources of both UHECRs and GRBs. Additionally, it turns out that the axion star is a plausible candidate for MACHO [16] because the value of the mass $M_a$ is suitable for explaining the observations of MACHOs. Since all of baryonic candidates for MACHOs seem to have serious difficulties [21], nonbaryonic ones like the axion stars would be favored.

We also discuss that the collisions generate monochromatic radiations with a frequency
$m_a/2\pi \simeq 2.4 \times 10^5 \text{ Hz.}$ Their flux is sufficiently large to be observed. With the detection of such radiations we can test our model and determine the axion mass.

It is reasonable to think that some of axion stars gravitationally attract matters, i.e. H and He in the Universe and have baryon contamination, while the other ones have no such contamination. Then, the axion stars with the baryon contamination produce protons as UHECRs in the collision with neutron stars. On the other hand the other ones produce photons as UHECRs, which are generated in fireball of electron-positron pairs. Therefore, UHECRs produced in our mechanism are either protons or photons.

In the section (2) we describe the properties of the axionic boson stars for latter conveniences. In the section (3) we explain how the axion star induces an electric field under an external magnetic field. In particular, we show that the axion star is electrically polarized in spite of the neutrality of the axion itself. In the section (4) we describe how the electric field can accelerate charged particles to the energies $\sim 10^{20} \text{ eV}$. Such a strong electric field can be produced only around a neutron star with magnetic field $> 10^{12} \text{ G}$. In the section (5) we explain a generation mechanism of GRBs by noting that the electric field dissipates rapidly its energy in conducting medium of neutron star. In the section (6) we show that our generation mechanism of UHECRs and GRBs gives the rate of the energy release consistent with the observations. In the section (7) we point out an observational signal of our mechanism, that is, electromagnetic radiations from axion star rotating around neutron star. The existence of such an observational signal is distinctive feature of our model. We summarize our results in the final section (8).

II. AXION STARS

Let us first explain axion stars (ASs), which are ones of most realistic boson stars. The axion is a Nambu-Goldstone boson associated with Pecci-Quinn symmetry, which was introduced for solving strong CP problem. The mechanism is the most plausible one for the problem. The symmetry is broken spontaneously at large energy scale, $f_{PQ} \sim 10^{12} \text{ GeV}$. But since the symmetry is anomalous, it is also broken dynamically by the effects of QCD instantons. Therefore, the axion obtains a mass, $m_a$.

The AS is a coherent object of the real scalar field $a(x)$ describing the axion. It is a gravitational bound state of axions represented by a solution [23,24] of the equation of the axion field coupled with gravity. An approximate form of the solution [24] without nodes is obtained in the limit of small mass $M_a << M_\odot$,

\[ a(x) = f_{PQ}a_0 \sin(m_a t) \exp(-r/R_a) , \]

where $t$ (r) is time (radial) coordinate and $f_{PQ}$ is the decay constant of the axion; there are solutions with nodes but their energies are much higher than that of this solution. The value of $f_{PQ}$ is constrained conventionally from cosmological and astrophysical considerations [12,13] such that $10^{10} \text{ GeV} < f_{PQ} < 10^{12} \text{ GeV}$. The axion mass $m_a$ is given in terms of $f_{PQ}$ such that $m_a \sim 10^{-2} \text{ GeV}^2/f_{PQ}$. But, when we assume entropy productions below the temperature 1 GeV in the early Universe, we may be released from the constraints [25]. Hereafter we assume that $f_{PQ} \sim 10^{16} \text{ GeV}$ or $m_a \sim 10^{-9} \text{ eV}$ for explaining huge characteristic energies of UHECRs and GRBs.
In the formula, $R_a$ represents the radius of an AS which has been obtained numerically in terms of mass $M_a$ of the AS;

$$R_a = 6.4 \frac{m_{pl}^2}{m_a^2} M_a \simeq 1.6 \times 10^5 \text{ cm} \, m_{g^{-2}} (10^{-1} \text{M}_\odot/M_a),$$

with $m_g = m_a/10^{-9} \text{ eV}$ and $m_{pl}$ is Planck mass. Similarly, the amplitude $a_0$ in eq(1) is represented such that

$$a_0 = 1.73 \times 10^2 \left( \frac{10^5 \text{ cm}}{R_a} \right)^2 m_g^{-1}.$$  

Therefore, we find that the solution is parameterized by one free parameter, either one of the mass $M_a$ or the radius $R_a$: Once we choose either of mass $M_a$ or radius $R_a$ of an AS, the whole properties of the AS are determined only in terms of the axion mass $m_a$ ($M_a$ and $R_a^{-1}$ should be less than a critical value mentioned soon below). It is also important to note that the solution is not static but oscillating with the frequency of $m_a/2\pi$. It has been demonstrated that there is no static regular solution of the real scalar massless field coupled with gravity. This may be general property of the real scalar massive field like the axion field. In fact, the oscillation in the solutions cause emission of electromagnetic radiations under a magnetic field, which is a general phenomenon expected in axions exposed to the magnetic field. On the other hand, static solutions of boson stars exist in the complex scalar field.

We should comment that the solution (1) can represent approximately solutions even with larger masses. More general solutions with larger masses have higher oscillation modes such as $\sin(3m_a t)$, $\sin(5m_a t)$ etc. But their amplitudes are much smaller than $a_0$.

The AS mass is determined by physical conditions under which the AS has been formed; how large amount of cloud of axions are cooled gravitationally to form the AS, etc.. The situation is similar to other stars such as neutron stars or white dwarfs. A typical mass scale in these cases is the critical mass: stars with masses larger than the critical mass collapse gravitationally into more compact ones or black holes. In the case of the AS, there also exists a critical mass $M_c$ which is given by

$$M_c \simeq 10^{-1} \text{M}_\odot m_{g^{-1}}.$$  

The ASs with masses larger than this one collapse into black holes. Therefore, we may adopt this critical mass $M_c$ as a characteristic mass scale of the ASs. The corresponding radius $R_a$ of the ASs with this critical mass is given such that $R_a \simeq 1.6 \times 10^5 \text{ cm}$. (The critical mass is the maximal mass, which ASs can take. Thus, their masses, in general, are smaller than this one. Since energies of ASs released in GRBs are given by their masses, the maximal energy in GRBs is given by the critical mass).

We wish to comment that a critical mass for stars like neutron stars, white dwarfs etc., represents order of masses they possess actually in the Universe. For example, the masses of the neutron stars are in a region of $1.0 \text{M}_\odot \sim 1.6 \text{M}_\odot$, while the critical mass of neutron star is given by about $2\text{M}_\odot$. Therefore, it is a reasonable assumption that the characteristic mass of the axion star is the order of the critical mass, $M_c$.

Although the gravitational cooling for ordinary star formation is in general ineffective because it is too slow process, it has been shown that the cooling is very effective for the real scalar axion field. Thus, the axion stars can be easily formed gravitationally in a
gas of the axions. It is reasonable to assume that the most of the axions in the Universe forms the axion stars.

Until now, we do not consider a case that the axion star has an ordinal matter, i.e. H and He. It is very natural to consider a possibility that the axion attracts gravitationally such matters after its formation. In the case the star is composed of the axions and the matters. The amount of the matters would be no more than the critical mass of the axion, unless it collapses into a black hole. It turns out below that such axion stars with matter contamination play role for emitting protons as UHECRs in the collision with neutron stars.

III. AXION STAR UNDER EXTERNAL MAGNETIC FIELD

Let us explain how an AS induces an electric field under an external magnetic field $\vec{B}$, in particular, that of a neutron star. Owing to the interaction between the axion and the electromagnetic field described by

$$L_{a\gamma\gamma} = c\alpha a(x)\vec{E} \cdot \vec{B} / f_{PQ}\pi,$$  \hspace{1cm} (5)

where the value of $c$ (of the order of unity) depends on axion models [28, 29, 13], the Gauss law is modified [30] such that

$$\partial \vec{E} = -c\alpha \partial \cdot \left( a(x)\vec{B} / f_{PQ}\pi \right) + \text{“matter”}.$$  \hspace{1cm} (6)

The last term “matter” denotes electric charges of ordinary matters. The first term in the right hand side represents an electric charge made of the axion. Although the axion is neutral, it can possess an electric charge under a magnetic field owing to the interaction eq(5). The interaction mixes electric and magnetic sectors. Thus, the axion star is electrically polarized under the magnetic field. (This polarization is oscillating and so there exists a corresponding oscillating current, $J_a = c\alpha \partial a(x)\vec{B} / f_{PQ}\pi$; it can be read by checking other Maxwell equations. Thus, radiations are emitted by the AS, which might be observable. We will discuss it in later section.) Accordingly, the electric field $\vec{E}_a$ is induced;

$$\vec{E}_a = -c\alpha a(x)\vec{B} / f_{PQ}\pi,$$  \hspace{1cm} (7)

with $\alpha \simeq 1/137$. Numerically, its strength is given by

$$E_a \sim 10^{15} \text{ eV cm}^{-1} B_{12} m_g,$$  \hspace{1cm} (8)

with $B_{12} = B/10^{12}$ G, where we have used the solution in eq(11) for the critical mass. Obviously, the spatial extension of the field is given by the radius $R_a \simeq 1.6 \times 10^5 m_g^{-1} \text{ cm}$ of the AS. Therefore, we find that the electric field is much strong around a neutron star with magnetic field $\sim 10^{12}$ G. This electric field is an engine of UHECRs in our model.

It should be mentioned that the existence of the electric field is originated in the coherence of axions composing axiom star. Incoherent axions can be converted into incoherent photons under a magnetic field. But, they never induce electric field with large spatial extension. This electric field causes UHECRs and GRBs. Thus, it is essentially important in our discussion that the axions are coherent in axiom stars.
We should also mention that electromagnetic radiations from the axion star are caused by the interaction which transforms axions to photons under magnetic field. This is the same phenomenon as one in Sikivie-type axion detectors; incoherent axions are converted into photons in the detector. In the case of coherent axions, oscillating electric current is induced due to the oscillation of the coherent axions themselves, as we have shown above. Hence, it is very general property for the solutions of axion star to oscillate in time.

IV. GENERATION MECHANISM OF ULTRA HIGH ENERGY COSMIC RAYS

The ultra high energy cosmic rays with energy $> 10^{20}$ eV pose a serious challenge for conventional theories of origin of cosmic rays. Such high energy cosmic rays can not travel in distance of more than 50 Mpc due to the interaction between the cosmic rays and the cosmic background radiation, or infrared background. But there are no candidate astrophysical sources like active galaxy nuclei in the directions of the UHECRs. Eight events of UHECRS have been detected and the detection rate is approximately once per year and per $100 \text{km}^2$. There are no conventional astrophysical and particle physical explanation for these observations.

Here we explain the events with a mechanism of the collision between axion stars and neutron stars with strong magnetic field $> 10^{12}$ Gauss. Under such a strong magnetic field the axion star induces strong electric field, which can accelerate charged particles to the energy $> 10^{20}$ eV. The electric field induced in the axion star is oscillating with the frequency, $m_a/2\pi \simeq 2.4 \times 10^5 m_a$ Hz. Thus a particle with electric charge $Ze$ can be accelerated by the field in a direction within the half of the period, $\pi/m_a$ or to a distance $\simeq R_a$ ($\sim \pi/m_a \times \text{light velocity}$), unless it collides with other particles within the period. Thus, the energy $\Delta E$ obtained by the particle is given by

$$\Delta E = Ze E_a \times \pi/m_a \times \text{light velocity} \sim 10^{20} Z_e V B_{12}.$$  

Therefore, the electric field can accelerate the charged particle to the energy $\sim 10^{20} Z_e$ eV. These charged particles may be baryons contaminated in AS or electron-positron pairs produced by the decay of the electric field itself. Note that the direction of the acceleration is parallel to the magnetic field. Thus the energy lose of the accelerated particles due to synchrotron emission is not important in the acceleration region.

Comment is in order. It seems apparently from eq(9) that stronger magnetic fields yield cosmic rays with higher energies. Stronger magnetic fields, however, induce stronger electric fields, which are unstable against electron-positron pair creations. Therefore, strong magnetic fields do not necessarily yield cosmic rays with higher energies.

If the particles collide with other particles on the way of acceleration, in other words, their mean free paths are shorter than $R_a$, they can not obtain such high energies. It is easy to see, however, that the mean free paths of quarks or leptons with much higher energies than their masses are longer than $R_a$ in magnetosphere of neutron star. This is because since cross sections, $\sigma$, of quarks or leptons with such energies $E$ behaves such as $\sigma \sim 1/E^2$, mean free paths $\sim 1/\sigma a$ is longer than $R_a \sim 10^5$ cm unless number density $n$ of particles around the AB is extremely large (i.e. $n > 10^{44}/\text{cm}^3$ for $E = 10^{20}$ eV). Obviously, under the electric field eq(8), the particles can obtain energies higher than their masses $\sim 1$ MeV by moving parallel to the electric field only in the distance of $\sim 10^{-9}$ cm.
The point in the acceleration is that as the electric field is much strong, charged particles can gain much energies by moving in a short distance. The mean free path becomes larger as the particles gain more energies. Thus, under the strong electric field the particles can gain effectively the energies without losing their energies.

As is well known, the strong electric field is unstable against electron-positron pair creations. Thus the field decays when the magnetic field of the neutron star is strong sufficiently. This implies that AS itself decays into the pairs.

Let us estimate the decay rate of the field and show that the AS decays before colliding directly with a neutron star whose magnetic field at surface is stronger than $10^{12}$ G. We also show that the AS can collide directly with a neutron star whose magnetic field is relatively weak $\leq 10^{10}$ G.

The decay rate $R_d$ of the field per unit volume and per unit time is given by

$$R_d = \frac{\alpha E_a^2}{\pi^2} \sum_{n=1}^{\infty} \frac{\exp\left(-m_e^2\pi n/e E_a\right)}{n^2}$$

where $m_e$ denotes electron mass. The rate is very small for an electric field much weaker than $m_e^2\pi \sim 4 \times 10^{16}$ eV/cm. The electric field of AS, however, can be very strong and it can be comparable to $m_e^2\pi$. Therefore, the rate is much large. Numerically, it is given by

$$R_d \sim 10^{47} B_{12}^2 m_9^2 \text{ cm}^{-3}\text{s}^{-1} \sum_{n=1}^{\infty} \exp(-0.7 \times 10^2 n/B_{12} m_9)/n^2.$$  

Since the spatial extension of the field is approximately given by $10^5 m_9^{-1}$ cm, the total decay rate $W$ of the field in AS is $\sim 10^{62} B_{12}^2 m_9^{-1}\text{s}^{-1} \sum_{n=1}^{\infty} \exp(-0.7 \times 10^2 n/B_{12} m_9)/n^2$. Numerically, it reads

$$W \simeq 10/\text{s} \text{ for } B_{12} = 0.5, \quad W \simeq 10^6/\text{s} \text{ for } B_{12} = 0.55, \quad W \simeq 10^{32}/\text{s} \text{ for } B_{12} = 1 \quad (12)$$

with $m_9 = 1$.

Therefore, we find that the AS decays very rapidly (or almost suddenly) when it approaches a region where the strength of the magnetic field reaches a critical value of about $10^{12}$ G. Hence, the AS evaporates before colliding with the neutron star whose magnetic field at the surface is stronger than $10^{12}$ G. The whole energy of the AS is transmitted to electron-positron pairs, each of which can obtain energies $\sim 10^{20}$ eV. These particles are emitted into a cone with very small solid angle. They form an extremely short pulse whose width being less than millisecond. Actually, when we suppose that the relative velocity of the AS is equal to light velocity, it decays approximately within a period of $10^{-4}\text{sec} \sim 10^{-5}\text{sec}$; in the period it passes the region where the magnetic field increases from $0.5 \times 10^{12}$ G to $10^{12}$ G. These leptons may be converted into baryons and photons through the interactions with themselves, interstellar medium or ejection of progenitor of the neutron star. In particular, the energies of the leptons are transmitted mainly to those of photons. Therefore, high energy photons are emitted as ultra high energy cosmic rays in the collision, when the magnetic field is sufficiently strong.

On the other hand, high energy protons are emitted in the collision between neutron star and axion star with matter contamination. Such a matter can be accelerated to the ultra high energy before the axion star decays. The amount of the protons emitted as UHECRs...
depends on the matter contamination in the axion star. We expect that almost of the same amount of protons with that of the leptons are emitted in such a collision.

We comment that the velocity of AS trapped gravitationally to a neutron star, is approximately given by the light velocity just when it collides with the neutron star. This is because an AS is trapped to a neutron star when the AS approaches it within a distance \( \sim 10^{11} \) cm where its potential energy dominates over its kinetic energy. After that, the AS goes around the neutron star, losing its potential energy and angular momentum by emitting gravitational and electromagnetic waves. Finally, the AS collides with it. Thus, the velocity of the AS reaches approximately the light velocity when it collides with the neutron star.

We have to examine the number density of the leptons produced during the decay of AS and have to check whether or not the density is less than \( 10^{45}/\text{cm}^3 \); the particles can not obtain the ultra high energies \( \sim 10^{20} \) eV unless the number density surrounding AS is not beyond the value quoted. They collide with other particles on the way of the acceleration and lose their energies. Suppose that the mass \( M_a \) of AS is transmitted to the energy of electron-positron pairs. Then, their number is given by \( \sim M_a/m_e \). They may be produced in the volume \( R_a^3 \) of AS. If we assume that they remain to stay in the volume after their production, the number density is \( \sim M_a/m_e R_a^3 \simeq 10^{44}/\text{cm}^3 \). Actually, the pairs escape in a direction pointed by the electric field within the life time of the field \( 10^{-4} \) sec \( \sim 10^{-5} \) sec. Thus, the real number density in AS is less than \( 10^{44}/\text{cm}^3 \). Therefore, we find that the number density of the pairs produced from the decay of AS is not so large to interrupt them obtaining the ultra high energies.

We can see from eqs(9) and (11) that the critical electric field depends on the factor of \( B_{12} \times m_9 \), while the energy \( \Delta E \) obtained by accelerated charged particles depends only on the factor of \( B_{12} \). Therefore, we find that if axion mass \( m_a \) is smaller than \( 10^{-9} \) eV, the maximal energy of cosmic rays can be larger than \( 10^{20} \) eV when a neutron star has strong magnetic field \( B > 10^{12} \) G. For instance, if \( m_a = 0.2 \times 10^{-9} \) eV, the cosmic rays with energies \( \sim 5 \times 10^{20} \) ZeV can be produced when a neutron star has magnetic field > \( 5 \times 10^{12} \) G at the surface.

\[ \text{V. GENERATION MECHANISM OF GAMMA RAY BURSTS} \]

Gamma ray bursts are observed daily from sources extending out to those of the most distant galaxies in the Universe. Duration of the bursts ranges from millisecond to thousand seconds. Pulse shape structures vary much from bursts to bursts. Typical energies of the gamma rays observed are of the order of 0.1 MeV. A mysterious puzzle of these bursts is the huge amount of energies released in the bursts. Some of the bursts carry energies \( \sim 10^{54} \) erg when spherical explosion from sources is assumed. Furthermore, baryon contamination in fire balls of the explosion is less than \( 10^{-4} M_\odot \). Therefore, it is very difficult to make realistic astrophysical models for explaining these properties, although it is believed optimistically that the origin of these phenomena would be some known astrophysical objects, such as merger of neutron star - neutron star, collapse of extremely massive star, etc.

Here, we explain a particle physical generation mechanism of gamma ray bursts. According to the mechanism, we can understand the problems of the huge energies released and the baryon contamination. But it is still difficult to understand the variant of the durations and the pulse shapes. The bursts are possibly produced in the collision between AS and neutron stars.
star with relatively small magnetic field such as \( \leq 10^{10} \) G. In such a weak magnetic field, the AS collides directly with the neutron star and dissipates its whole energy in an outer crust of the neutron star. Actually, the decay rate \( W \) of the electric field is negligibly small for the case of the weak magnetic field \( \leq 10^{10} \) G. Thus the AS does not decay before colliding directly with such a neutron star. The AS, however, decays in magnetized conducting medium such as the outer crust of neutron star. Namely the electric field of the AS induces electric current in the crust, which dissipates its energy owing to finite electric conductivity of the crust. Thus, the AS decays very rapidly by dissipation its energy. Consequently, particles of the crust are emitted as a jet in the collision, which forms fireball emitting gamma ray bursts.

We will estimate the rate of the energy dissipation in the outer crust with use of the conductivity, \( \sigma = 10^{26}/s \) \([32]\). The value of the conductivity, in general, depends on physical parameters of the crust such as temperature, composition, density, etc. The value of \( \sigma \) we use, however, is a typical one of the crust and does not vary so much even if we change the parameters of the density, temperature, or composition within a reasonable range.

We calculate \([10, 18]\) the rate \( W_{\text{dis}} \) of the dissipation per unit time and unit volume as follows,

\[
W_{\text{dis}} = \int_{\text{AS}} \sigma E_a^2 d^3 x / \int_{\text{AS}} = 4c^2 \times 10^{61}/(4\pi/3R_a^3) \text{ erg/s} \frac{\sigma}{10^{26}/s} \frac{M_a}{10^{-1}M_{\odot}} \frac{B^2}{(10^{10}G)^2} \quad (13)
\]

\[
\simeq 2.4 \times 10^{45} \text{ erg/s cm}^3 \frac{\sigma}{10^{26}/s} \frac{B^2}{(10^{10}G)^2} m_5^2, \quad (14)
\]

where we have used the solution in eq(1) for the critical mass. The integration has been performed over the volume \( ( = 4\pi R_a^3/3 ) \) of an AS, which has been supposed to be involved completely in the conducting medium. Thus it represents an average rate of the energy dissipation in the outer crust.

We find that the energy dissipation proceeds very rapidly in the medium. We compare the rate with the energy density of the AS, which is given by \( 10^{37} \) erg/cm\(^3\). Hence, we find that the AS dissipates the whole energy \( \sim 10^{53} \) erg in the outer crust even if it rushes into the medium with the light velocity; the depth of the crust is equal to several hundred meters. It never reaches the core of the neutron star.

This very rapid energy release leads to the ejection of the particles composing the crust. The ejection could be emitted into a cone with small solid angle as a jet. This is because the particles (mainly irons) of the neutron star are accelerated and emitted in the direction parallel to the strong electric field \( \sim 10^{13} B_{10} \) eV/cm. The particles are accelerated to energies \( \sim 10^{18} \) eV, while their characteristic energies inside the crust are \( \sim 10^6 \) eV. Thus, we expect that solid angle of the jet is much small, although the particles do not necessarily obtain such high energies because of loosing energies by the collisions with others. The fact that the whole energy of AB is dissipated only in the outer crust, implies that the ejection are only particles composing the crust. Thus a fraction of the baryon contamination in the jet is less than \( 10^{-5} M_{\odot} \) as required observationally. We expect that a large amount of neutrinos with high energies is also produced in the collision with the rapid energy dissipation. The neutrinos burst can be observed in future observatory although it has lost the direction pointing to a source of a GRB in which it was born. This is our generation mechanism of gamma ray bursts with energies \( \sim 10^{53} \) erg.
In the above case, the AS dissipates its whole energy in the first collision. On the other hand, an AS may collide several times with a neutron star when its mass is much smaller than the critical mass \( \sim 10^{-1} M_\odot \); the mass has been assumed as a characteristic mass scale of ABs. We see from the general formula eq(2) of \( R_a \) that the radius of the AS with smaller mass than the critical one is larger than the critical radius \( \sim 10^5 \) cm. For example, if its mass is given by \( 10^{-2} M_\odot \), the radius is about \( 10^6 \) cm. This is comparable to the radius of the neutron star. Hence, the collisions may occur several times. Such an AS never loose its whole energy in the first collision. How many times the collisions occur depends on the collision parameters. Unless the centers of both stars are on the straight line parallel to the relative velocity, the whole energy of AS does not dissipate in the first collision. There could be several collisions after the first collisions. The electric field induced in the AS is also small compared with the one mentioned above; \( E_a \sim 10^{11} \) eV cm\(^{-1} \) \( B_{10} m_9 \), for \( M_a = 10^{-2} M_\odot \). Thus, the energies of the particles emitted from the neutron star are much smaller than \( 10^{18} \) eV. Furthermore, since the rate of the energy dissipation becomes smaller in the case of AS with smaller mass, the rate of the energy release is also smaller. It means that jet emitted in the collision is softer; its flux (and energies of each particles) is smaller than that of a jet emitted from the collision of AS with the critical mass. The total energies released (\( \sim 10^{52} \) erg for \( M_a = 10^{-2} M_\odot \)) are also smaller than \( 10^{53} \) erg. We expect that these collisions generate gamma ray bursts with long duration and soft gamma rays. On the other hand, gamma ray bursts with short duration and hard gamma rays are produced in the first collision in which the whole energy is dissipated completely.

We should comment that when the axion star with much matter contamination collides, the jet ejected from the collision may contain baryon contamination much larger than \( 10^{-5} M_\odot \). Thus in such a collision, Lorentz factor of the jet is not so large that gamma ray bursts may not be produced.

VI. RATE OF ENERGY RELEASE IN UHECRS

We now wish to estimate an energy release rate in the collisions between ASs and neutron stars. We assume that UHECRs are produced in the collision of neutron stars with relatively strong magnetic field \( > 10^{12} \) G and that GRBs are produced in the collision of neutron stars with relatively weak magnetic field \( \leq 10^{10} \) G. Thus it is assumed that all of neutron stars are divided into those with \( B > 10^{12} \) G and those with \( B \leq 10^{10} \) G. We take the fraction of the neutron stars with \( B > 10^{12} \) G to be \( f \); \( 0 < f < 1 \). Although the collisions may occur, in general, in the whole Universe, we estimate the rate of the collision which arises in a galaxy. Thus the real rate is larger than a rate in our estimation. Furthermore, we assume that the dark matter is composed mainly of axion stars. In particular a hale is composed of the axion stars. The estimation, however, involves several ambiguities associated with number density of neutron stars, energy density of dark matter or velocity of ASs in the Universe etc. Therefore the estimation does not lead to a conclusive result although our result is consistent with the observations [1].

First we assume that almost of all neutron stars are mainly located around a galaxy in which they were born. We also assume that their distribution is uniform in a halo of the galaxy whose size is supposed to be given by 50kpc. Our result does not depend on the precise value of the size although it depends on mean energy density of the dark matter in
the halo. Thus the collision between neutron star and axion star arises in the halo. The number of the neutron stars located around a galaxy is supposed to be $\sim 10^9$; the present rate of appearance of supernovae in a galaxy is about $0.1 \sim 1$ per 10 year and the rate of the appearance could be larger in early stage of the galaxy than the one at present. Therefore, the number density $\rho$ of the neutron stars would be given such that $\rho \simeq 10^9/(50 \text{kpc})^3$.

All of these neutron stars are assumed to possess either strong magnetic field $> 10^{12} \text{ G}$ or weak magnetic field $\leq 10^{10}$. Furthermore, to estimate the rate of the energy release we need to know average density $\epsilon$ of the dark matter, i.e. density of axion stars. Here we use a value [12] of $\epsilon \simeq 0.5 \times 10^{-25} \text{ g/cm}^3$, which represents a local density of our halo: Our result depends on $\epsilon$ linearly. Using these parameters we can estimate the rate owing to the collision between the AS and the neutron star. The collision takes place as a result of AS losing angular momentum and potential energy soon after AS being trapped gravitationally to a neutron star. Thus, we estimate the cross section for a neutron star to trap an AS in the following. Namely an AS is trapped by the neutron star when the AS approaches the neutron star within a distance $L_c$ in which its kinetic energy $M_a v^2/2$ is equal to its potential energy $1.5 \times M_\odot M_a G/L_c$ around the neutron star. $G$ is gravitational constant. Here the mass of the neutron star and the relative velocity $v$ are assumed to be $1.5 \times M_\odot$ and $3 \times 10^7 \text{ cm/s}$, respectively. Thus, the cross section is found such as $L_c^2 \pi$ with $L_c \simeq 6 \times 10^{11} \text{ cm}$. The lose of its potential energy and angular momentum would be caused by the emission of gravitational and electromagnetic waves; electromagnetic radiations arise due to the oscillating current $J_a$. It also takes place by the interaction between the electric field of AS and plasma wind from neutron star. The detail calculation has not yet been done. It will be clarified in future publication.

Anyway, under the assumptions, we obtain the rate of the collision between neutron star and axion star per Mpc$^3$ and per year,

$$\left(\frac{\epsilon}{10^{-1} M_\odot} \times \rho \times L_c^2 \pi \times v \times 1 \text{ year}\right)/(20)^3 \simeq 3 \times 10^{-10} /\text{Mpc}^3 \text{ year}. \tag{15}$$

where we have obtained the rate per a galaxy with its volume $(50 \text{kpc})^3$ and have divided it with $(20)^3$ to get the rate per Mpc$^3$. This rate is divided into the rate of production of UHECRs and the rate of production of GRBs.

Here we comment that the rate heavily depends on the relative velocity $v$: $L_c^2 \times v \sim v^{-3}$. Thus if we choose a value $v = 2 \times 10^7 \text{ cm/s}$, the rate is given by $\sim 10^{-9} /\text{Mpc}^3 \text{ year}$. Thus our result involves an ambiguity of the order of 10.

Since the energy of $\sim 10^{53} \text{ erg}$ is released in the collision, we find that the rate of the energy release as UHECRs is given by

$$\sim (3 \times 10^{43} \sim 10^{44}) f \text{ erg/Mpc}^3 \text{ year}. \tag{16}$$

where we assumed that the whole energy released is transmitted to UHECRs or GRBs. Our result does not include the contributions from collisions arising far outside of a galaxy. The real rate is larger than the rate in our estimation. Thus we may conclude that the result roughly agrees with the observation. It is well known that both rates of energy release in UHECRs and GRBs are nearly the same with each other. It implies that the fraction of the neutron stars with $B > 10^{12} \text{ G}$ is nearly the same with the fraction of neutron stars
with $B \leq 10^{10}$. Taking account of several ambiguities in the parameters used above and the rough estimation, we can say simply that our model can explains roughly the observations.

VII. OBSERVATIONAL SIGNAL OF AXION STARS

We have discussed our model for generation mechanisms of UHECRs and GRBs. These are generated in the collision between axion star and neutron star. An significant question is how we can check observationally our model. Since we have supposed that dark matter in Universe is composed mainly of axion stars, observation of the axion stars is important for checking validity of our model. There are several attempts of the detection of the axion itself. These attempts use axions conversion into photons under magnetic field in terrestrial experiments. But there are no attempts to observe axion stars. Since a collision between an axion star and the earth is very rare, we need to detect signals from the axion stars located far away from the earth.

Here we wish to discuss the observation of two types of signals from the axion stars. One is associated with gravitational lensing and the other one associated with monochromatic radiations from the ASs.

It was very intriguing to detect microgravitational lens effects associated with the halo of our galaxy. Since the first observations have been reported, several candidates for MACHOs have been proposed. Observationally, it is necessary for the candidates to have masses $M$ roughly such as $0.1 \times M_\odot < M < 0.7 \times M_\odot$. Since we have assumed that the halo of our galaxy is composed of ASs and their mass is $\sim 10^{-1}M_\odot$, the ASs are plausible candidates for the MACHOs. As has been recognized, baryonic candidates like white dwarfs, neutron stars, etc. have serious problems. Nonbaryonic candidates are favored [21]. The problems are associated with chemical abundance of carbon and nitrogen in the Universe: If these baryonic stars are MACHOs, an overabundance of the elements is produced far in excess of what is observed in our galaxy. Hence, the ASs are theoretically the most fascinating candidates for the MACHOs as nonbaryonic ones. They are also candidates for the generators of both UHECRs and GRBs. If the most favorable mass of the MACHO is $0.5M_\odot$, we need to choose $m_a \approx 0.2 \times 10^{-9}$ eV since the mass of the ASs is given by $\approx 10^{-1}M_\odot/m_a$. We note that smaller axion mass leads to stronger electric field as well as larger mass of AS. Thus, it yields higher energies of the UHECRs, $\sim 5 \times 10^{20}$ eV and of GRBs, $\sim 5 \times 10^{53}$ erg than the ones we have claimed above. Accordingly, the determination of the mass of MACHOs gives the upper limit of both the energies of the ultra high energy cosmic rays and the energies released in the gamma ray bursts in our mechanism.

We point out another way of the observation of the axion stars. Since the electric field $E_a$ as well as electric current $J_a$ induced in ASs is oscillating, electromagnetic radiations are emitted [24,34]; the frequency of these monochromatic radiations is $\approx 2.4 \times 10^5 m_9$ Hz (their wave length is given by $\sim 1.3 \times 10^5/m_9$ cm.) Their flux is stronger as the magnetic field imposed on AS is stronger. AS revolves around neutron star, loosing its potential energy and angular momentum, and then collides with it. In the revolution, AS emits the radiations with flux depending on the strength of the magnetic field. Hence, we expect that such radiations with maximal flux can be detected just in advance of UHECRs. Their flux is strongest among others just before UHECRs being emitted; the magnetic field is strongest
when the AS decays into charged particles. It is easy to estimate their luminosity \([34]\) by evaluating gauge potential \(A_i\),

\[
A_i = \frac{1}{R_0} \int_{AS} J_a(t - R_0 + \vec{x} \cdot \vec{n}) \, d^3x = \frac{c_o \sigma a_0 B_i}{\pi R_0} \int_{AS} \sin m_a(t - R_0 + \vec{x} \cdot \vec{n}) \exp(-r/R_a) \, d^3x \quad (17)
\]

\[
= \frac{4c_o m_a a_0 B_i}{R_0} \frac{R_a^3}{(m_a^2 R_a^2 + 1)^2} \sin m_a(t - R_0) , \quad (18)
\]

where \(R_0 (\vec{n})\) denotes a distance (direction) between (from) the neutron star and (to) the earth. We have integrated the current \(J_a\) over the AB, which is located near the neutron star. Thus, the luminosity \(L\) of the radiations is given by

\[
L = 4c^2 \alpha^2 a_0^2 B^2 \frac{R_a^6}{(m_a^2 R_a^2 + 1)^4}
\]

\[
\simeq 6.7 \times 10^{41} B_{12}^2 \text{erg/s}, \quad (19)
\]

with \(c = 1\). If the emission arises in a distance \(\sim 10\) Mpc from the earth, we obtain the flux at the earth, \(\sim 10^9\) Jy \(B_{12}^2/m_0\); we have assumed that the velocity of the AS revolving is \(\sim 0.1 \times\) light velocity. Although the possibility of observing the radiations is very intriguing, it might be difficult to detect the radiations with such a low frequency because they could be absorbed by interstellar ionized gases before arriving the earth. \(v\)

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