# Magnetic monopole noise in magnetars

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Magnetic monopoles, if they exist, would be produced amply in strong magnetic fields via the Schwinger process. Such circumstances arise in neutron stars with a strong magnetic field—magnetars. It is argued in this article that pair production of magnetic monopoles in magnetars must be accompanied with hypothetical magnetic monopole noise. It is shown that magnetic monopole noise, if it exists, must have Poisson statistics and "white" spectrum. Magnetic monopole noise leads to magnetic field fluctuations, which may be related to spin period fluctuations of magnetar. Estimations show that such period fluctuations for sufficiently light magnetic monopoles, if they are produced in the magnetic field of magnetar, can be measured experimentally.

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## I. INTRODUCTION

An elementary particle with only one magnetic pole (a north pole without a south pole or vice versa), called magnetic monopole, has never been seen in real world. But there are strong theoretical arguments why magnetic monopoles should exist.

Modern interest in magnetic monopoles is focused on the quantum field theory, notably Grand Unified Theories and superstring theories, which predict the existence of the possibility of magnetic monopoles. Paul Dirac [1] proposed in 1931 that the magnetic monopole with an attached Dirac string may exist in quantum electrodynamics by their phenomenon of electric charge quantization. It was shown by G. ‘t Hooft [2] and Polyakov [3] in 1974 that a magnetic monopole could be regarded as topological excitations in a quantum field theory due to the spontaneous symmetry breaking mechanism. The quantized magnetic charge was interpreted as the topological charge of the magnetic monopole.

There are in condensed matter physics topological objects that imitate magnetic monopoles also. Magnetic monopoles in spin ice are effective quasiparticle excitations with magnetic charges acting as isolated magnetic north and south poles. It was predicted in [4] that there should be magnetic monopole noise in spin ice caused by monopole-antimonopole generation-annihilation processes. Recent measurements [5] of the spectral density of magnetic-flux noise gave the experimental confirmation of theoretical predictions [4]. That stimulated further investigations in this area [6,7,8].

Quantum electrodynamics predicts that, in a strong electric field, electron-positron pairs are produced by the Schwinger process. If magnetic monopoles exist, monopole-antimonopole pairs would be similarly produced in strong magnetic fields by the electromagnetic dual of this process [9]. Such circumstances (strongest magnetic fields in the Universe) arise in neutron stars, called magnetars.

A magnetar is a type of neutron star believed to have an extremely strong magnetic field ($\sim 10^9$ to $10^{11}$ T, or $\sim 10^{13}$ to $10^{15}$ G) [10].

It is argued that the generation of the magnetic monopoles will dissipate the energy of the magnetic field of the neutron star [11,12].

In [11], it is noticed that very young pulsars can be a source of magnetic monopoles. Half of these monopoles are accelerated toward the interstellar medium by the pulsar magnetic field, and the others are likely to be trapped inside the neutron star crust. This leads to a decrease in the pulsar magnetic field, which would imply that the characteristic age $P/2\dot{P}$ may not give the true age of the pulsar. Furthermore, magnetic monopoles accumulated under a polar cap of the neutron star perturbates the pulsar electrodynamics.

For the magnetar case, the authors [12] calculated how the presence of monopoles in the interior of a star would affect the rate at which the energy of the star's magnetic field is dissipated. By plugging into this calculation an observational estimate of the maximum magnetic field of magnetar, the researchers obtained a lower bound of 0.7 GeV on the mass of monopoles with twice the minimum magnetic charge.

Additional possible processes (effects), that may accompany the generation of the magnetic monopoles in magnetar, are discussed now.

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For this, a possible magnetic monopole noise in magnetar is discussed by analogy with magnetic quasimonopole noise in spin ice [4,5].

Thus, the main idea of the present paper is to implement the approach used in [4] to describe the possible noise of real magnetic monopoles in some exotic cosmic objects such as neutron stars with a strong magnetic field—magnetars.

The theoretical model of magnetic monopole noise in magnetar is discussed in Sec. II.

Some estimations, related to the model from Sec. II, are presented in Sec. III.

Possible relations of such noise with other effects are discussed briefly in Sec. IV.

The results are summarized in Sec. V.

## II. MODEL

In this paper, we consider magnetic monopole-antimonopole pair production in strong magnetic fields of magnetars.

Inflation would have diluted away any preexisting magnetic monopoles [13,14]. Thus, we do not discuss here "relic" magnetic monopoles.

We consider magnetic monopole pair production in the strong, long-lived magnetic fields present around magnetars. Sufficiently light magnetic monopoles would be produced by Schwinger pair production and dissipate the magnetic field.

This approach is model-independent in the sense that it applies to both elementary and composite (e.g., 't Hooft-Polyakov) monopoles.

The critical field strength for monopole pair production (classical and quantum Schwinger pair production of pointlike monopoles) is approximately equal to $B_{\mathrm{Schwinger}} \approx 4\pi m^2/q_m^3$, where $m$ is the monopole mass and $q_m$ is the magnetic charge of the monopole [15].

According to Dirac, the minimum magnetic charge is equal to $2\pi/e$, where $e$ is the charge of the positron. But there may exist monopoles with greater charge [12].

Magnetic fields have been estimated to be up to $B_{\mathrm{Magnetar}} \approx 10^{11}\ \mathrm{T} \approx 10^{15}\ \mathrm{G}$ for the magnetars [16]. Magnetic monopoles present in such circumstances would be accelerated by the magnetic field thuswise dissipating its energy.

The magnetic field of a neutron star can be approximated as dipolar [17]. We focus on the magnetic fields above the surface of the star, which are fairly well established. Also, we assume that on the microscopic scale the magnetic field can be treated as constant. We do not consider interactions between magnetic monopoles and matter particles [18–21] and other possible effects.

Here, we use the result of [12], where it was noticed that for typical magnetar mass and radius parameters, at the surface of the star, where the gravitational field is strongest, the magnetic force dominates over the gravitational one for magnetic monopoles with masses much less than $10^{19}$ GeV. In this regime magnetic monopoles will be accelerated by the magnetic field to nearly the speed of light and will escape both the gravitational attraction of the star and the dipolar magnetic field.

The energy density of the magnetic field acts locally as a source of magnetic monopoles. If the density of magnetic monopoles is low enough, which indeed it will turn out to be, we can ignore their annihilation. The presence of a uniform magnetic field near the surface of a magnetar will separate the monopole and antimonopole and hence reduce the annihilation rate, e.g. the magnetic field would therefore pull one of them to the surface of the star and expel the other one into space [9]. Thus, the number density of produced magnetic monopoles $N$ is to be proportional to the rate of Schwinger pair production [12].

The presence of the magnetic monopoles, being accelerated by the magnetic field, will dissipate the energy of the magnetic field at the rate [12]

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{B^2}{2}\right) = -\mathbf{J_M}\mathbf{B}, \tag{1}$$

where $\mathbf{B}$—magnetic field, $\mathbf{J_M}$ is the magnetic current density.

We can reach from (1) an obvious result, showing that changes of magnetic field are proportional to the magnetic current density:

$$\frac{\mathrm{d}B}{\mathrm{d}t} = -J_M. \tag{2}$$

Here $J_M$ is determined as $J_M = q_m N v$, where $q_m$ is the magnetic charge and $v$ is the spatial velocity. The magnetic current will be aligned with the magnetic field.

It is shown in [12] that $\mathrm{d}B/\mathrm{d}t \approx -q_m r \Gamma$, where $r$ is the coefficient, which is of the order of the radius of the spatial region and $\Gamma$ is the rate of pair production in unit volume.

Actually, half of these monopoles are accelerated toward the interstellar medium by the magnetar magnetic field, and the others are likely to be accumulated at both poles of the magnetar. The monopoles, which are accelerated toward the interstellar medium, take up their energy from the magnetic field. Accumulated at both poles magnetic monopoles induce a decrease in the dipole magnetic field too.

M. Bonnardue and A. K. Drukier in [22] have shown that both processes may be described by an equation of type (2). Thus, in the following, we will approximate the two processes by Eq. (2).

Consider the fast dynamo process, argued in [23] to be responsible for the strong magnetic fields in magnetars. In the presence of this process the rate of change of the magnetic field (2) is modified to [12]

$$\frac{\mathrm{d}B}{\mathrm{d}t} = -J_M + \frac{B}{2\tau_D}, \tag{3}$$

where $\tau_D$ is the characteristic enhancement time of the dynamo. For sufficiently small magnetic fields the rate, $\Gamma$, is strongly exponentially suppressed, and the dynamo action dominates. Conversely, the exponential dependence of $\Gamma$ on $B$ means that $\Gamma$ will always dominate at sufficiently large values of $B$.

At first step we neglected the fast dynamo process. Here, we assume that the Schwinger pair production mechanism will always dominate at sufficiently large values of $B$ [12].

If we consider the magnetic current density $J_M$ more precisely we can notice, that current density $J_M$ originates from the discrete nature of magnetic charge. Thus, we can approximate the magnetic monopole current density, which is formed by monopoles that are produced and accelerated in the magnetar magnetic field in the interstellar medium, as a sum $J_M(t) \propto \sum_j q_m \delta(t - t_j)$, where $\delta$ is Dirac delta function, and $t_j$ are the random times of the monopole production.

The next step deals with statistics of this process.

We consider the number of monopoles $N$, which have generated up to time $t$, to be a statistical quantity described by the probability $P(N, t)$. Then, assuming the probability that a monopole will generate in the time interval between $t$ and $t + \Delta t$ is independent of $t$ and $N$, its only dependence can be on $\Delta t$. By choosing an appropriate constant $\lambda$, we can write $P(N \to N + 1, \text{in time}\, \Delta t) = \lambda \Delta t$, so that $P(N, t + \Delta t) = P(N, t)(1 - \lambda \Delta t) + P(N - 1, t)\lambda \Delta t$, and taking the limit $\Delta t \to 0$ we obtain $\partial P(N, t)/\partial t = \lambda[P(N - 1, t) - P(N, t)]$. From this equation we find [24]

$$P(N, t) = \frac{(\lambda t)^N}{N!} \mathrm{e}^{-\lambda t}. \tag{4}$$

As we can see from (4) Poisson statistics describe this process. This process is analogous (in form, but not in physical origin) to the well-known shot noise, which arises, for example, in the case of thermionic emission from cathode in vacuum devices (and in solid-state devices).

The spectral density of the process described above and obeying statistics (4) is equal to

$$S_{JM}(f) = \frac{2\lambda q_m^2}{S} = \frac{2 q_m J_{M0}}{S}. \tag{5}$$

Here $\lambda \propto r\Gamma$ and $J_{M0}$—average current, $S$—the fraction of the magnetar surface area through which magnetic monopoles may escape. Poisson noise has a "white" spectrum.

However, no monopoles have been verifiably detected to date. Therefore we have to speak about the magnetic monopole noise only hypothetically. And, of course, magnetic monopole noise cannot be measured directly. Thus, it is necessary to specify the indirect processes that may accompany this phenomenon.

One of the possible manifestations of magnetic monopole noise is magnetic field fluctuations.

Magnetic current has the stochastic nature; thus Eq. (2) must be rewritten in the form

$$\frac{\mathrm{d}(B_{\text{slow}} + \Delta B)}{\mathrm{d}t} = -J_{M0} + \xi(t), \tag{6}$$

where $\xi(t)$ is the shot noise of magnetic monopoles, and $B_{\text{slow}}$ is a relatively slow (in comparison with fluctuations of magnetic field $\Delta B$) change of magnetic field, caused by the average magnetic current density $J_{M0}$. Fluctuations of magnetic field $\Delta B$ are caused by the stochastic process of magnetic monopole generation (production) $\xi(t)$. Thus,

$$\frac{\mathrm{d}(\Delta B)}{\mathrm{d}t} = \xi(t). \tag{7}$$

From stochastic Eq. (7) we can find the spectral density of magnetic field fluctuations:

$$S_{\Delta B}(f) = \frac{S_{JM}(f)}{(2\pi f)^2} = \frac{2 q_m J_{M0}}{S(2\pi f)^2}. \tag{8}$$

As we can see from Eq. (8), the spectral density proportional to $1/f^2$ (so called "red noise").

Moreover, from (7) we can reach a relation of magnetic field fluctuations with magnetic monopole current density fluctuations:

$$\Delta B(t) = \Delta B(t_0) + \int_{t0}^{t} \xi(u) du. \tag{9}$$

We mentioned above that on the microscopic scale the magnetic field can be treated as constant. But in greater scales the magnetic field may be nonuniform, and thus magnetic field fluctuations and relation (8) may have a local character.

We can consider the fast dynamo process now. There is the point in Eq. (3), at which the two effects are approximately equal; thus the right-hand side of this equation is close to zero. If the change (growth) of magnetic field, caused by the fast dynamo process is relatively fast, we must add the term $\Delta B/(2\tau_D)$ into the right part of Eq. (7). Thus, we can estimate spectral density of magnetic field fluctuations in the presence of the dynamo process

$$S_{\Delta B}(f) = \frac{S_{JM}(f)}{[(\frac{1}{2\tau_D})^2 + (2\pi f)^2]}. \tag{10}$$

Short characteristic dynamo time $\tau_D$ is approximately equal to 1–10 seconds; thus the first term in the denominator is negligible at relatively high frequency.

Magnetic fields in stars can be directly measured by the Zeeman splitting of spectral lines. Such direct measures are not possible in magnetars.

The main signature of the magnetic field in neutron stars is the loss of rotational energy due to the electromagnetic torque. Thus, the rotational properties give an estimate of the large-scale dipolar magnetic field. Taking into account periods and period derivatives, typically $P \sim 1 - 12$ s and $\dot{P} \sim 10^{-14} - 10^{-10}$ ss$^{-1}$ [25], one can infer magnetic field intensities up to $B \sim 10^{11}\mathrm{T} \sim 10^{15}$ G (see Introduction). In a few cases, x-ray spectra show hints for cyclotron lines, from which the value of the surface magnetic field can be estimated.

In general, the relation between spin period $P$ and its derivative with surface magnetic field can be written in the form

$$P\dot{P} = KB^2, \tag{11}$$

with coefficient of proportionality $K$, which may be considered as a constant. We can formally add magnetic field fluctuations to the magnetic field in Eq. (11):

$$(P + \Delta P)(\dot{P} + \Delta\dot{P}) = K(B + \Delta B)^2. \tag{12}$$

After linearization we have

$$\Delta\dot{P} + \frac{\dot{P}}{P}\Delta P = \frac{2KB}{P}\Delta B. \tag{13}$$

Denote $A \equiv \dot{P}/P, \eta(t) \equiv (2KB/P)\Delta B$; thus

$$\Delta\dot{P} + A\Delta P = \eta(t), \tag{14}$$

with

$$S_\eta(f) = \left(\frac{2KB}{P}\right)^2 S_{\Delta B}(f). \tag{15}$$

Thus, the spectral density of period fluctuations is

$$S_{\Delta P}(f) = \frac{S_\eta(f)}{A^2 + (2\pi f)^2}. \tag{16}$$

In the final form this yields

$$S_{\Delta P}(f) = \left(\frac{2KB}{P}\right)^2 \frac{2q_m J_{M0}}{S((\dot{P}/P)^2 + (2\pi f)^2)(2\pi f)^2}. \tag{17}$$

For the interested frequency band, term $(\dot{P}/P)^2$ in Eq. (17) is negligibly small, and this equation for the spectral density of $\Delta P$ can be simpified: $S_{\Delta P}(f) = (2KB/P)^2(2q_m J_{M0}/(S(2\pi f)^4))$.

We can estimate $\Delta P$ now. Assuming terms in the left part of Eq. (13) to be of the same order, i.e. $\Delta P \sim (P/\dot{P})\Delta\dot{P}$, we can estimate $P$ fluctuations $\Delta P \approx (KB/\dot{P})\Delta B$. For more precise calculation, one may use Eq. (17) and estimate the variance of absolute fluctuations of $\Delta P$ in the investigated frequency band, and find the root-mean-square (effective) value of $\Delta P$.

## III. ESTIMATIONS

If magnetic monopoles exist, they would be pair produced in a sufficiently strong external magnetic field. The rate per unit space-time volume is [26,27,9]

$$\Gamma = \frac{q_m^2 B^2}{8\pi^3} \exp\left(-\frac{\pi m^2}{q_m B} + \frac{q_m^2}{4}\right). \tag{18}$$

In the case under study, it is $c = \hbar = \varepsilon_0 = 1$. Before we make some further estimations, we need to choose the system of units. The rate dimension of the pair production per unit volume in (18) is $\mathrm{m}^{-3} \cdot \mathrm{s}^{-1}$. We need to restore the "invisible" conversion factor to match the dimensions on both sides. Our aim is to recover all constants $c$, $\hbar$ and $\varepsilon_0$ and bring the final result in the SI units. The restoration of all constants $\hbar$ and $c$ in the Schwinger formula (18) yields

$$\Gamma = \frac{q_m^2 B^2}{8\pi^3\hbar^2 c} \exp\left(-\frac{\pi m^2 c^3}{q_m B\hbar} + \frac{q_m^2}{4\varepsilon_0\hbar c^3}\right), \tag{19}$$

where $\varepsilon_0$ is electric constant.

We can find, from (5), (8) and (19), the spectral density of magnetic field fluctuations (in the SI units) as

$$S_{\Delta B}(f) = \frac{2\mu_0^2 q_m^4 B^2 r}{8\pi^3 S\hbar^2 c(2\pi f)^2} \exp\left(-\frac{\pi m^2 c^3}{q_m B\hbar} + \frac{q_m^2}{4\varepsilon_0\hbar c^3}\right), \tag{20}$$

where $\mu_0$—magnetic constant.

Thus, we can estimate the variance of absolute fluctuations of the magnetic field in the investigated frequency band $\sigma_{\Delta B}^2 = \int_{f\,\mathrm{min}}^{f\,\mathrm{max}} S_{\Delta B}(f)\,\mathrm{d}f$. From here we find the root-mean-square (effective) value $\Delta B_{\mathrm{eff}} = \sqrt{\sigma_{\Delta B}^2}$:

$$\Delta B_{\mathrm{eff}} = \frac{\mu_0 q_m^2 B r^{1/2}}{2\sqrt{2}S^{1/2}\pi^2\hbar c^{1/2}} \left(\frac{1}{2\pi f_{\mathrm{min}}} - \frac{1}{2\pi f_{\mathrm{max}}}\right)^{1/2} \times \exp\left(-\frac{\pi m^2 c^3}{2q_m B\hbar} + \frac{q_m^2}{8\varepsilon_0\hbar c^3}\right). \tag{21}$$

Calculation for the field of magnetar of Ref. [12] gives a mass bound for magnetic monopole $m \gtrsim 0.31$ GeV for the Dirac charge $q_m = q_D = 2\pi/e \approx 20.7$, and a bound $m \gtrsim 0.70$ GeV for the charge $q_m = 2q_D$. If there were to exist magnetic monopoles lighter than these lower bounds, their production and acceleration would strongly dissipate the magnetic field before it could ever reach $B_{\mathrm{Magnetar}}$.

If we take $B \approx B_{\mathrm{Magnetar}} \approx 5 \times 10^{11}\mathrm{T} \approx 5 \times 10^{15}$ G [12], $r \approx 10$ km, the radius of the magnetar, $S = 4\pi r^2$, area, which is of the order of the magnetar surface, we derive the following estimations for field fluctuations in the frequency range $0.1\ \mathrm{Hz} \le f \le 1$ MHz (typical band for low frequency noise measurements): $\Delta B \sim 1$ T for $m \approx 0.337$ GeV (value close to mass bound from Ref. [12]) for $q_m = q_D$; $\Delta B \sim 100\ \mu$T for $m \approx 0.354$ GeV for $q_m = q_D$.

For $\Delta P \approx (KB/\dot{P})\Delta B$, taking $\dot{P} \sim 10^{-10}$ ss$^{-1}$ and using relation $B = 3.2 \times 10^{19}\sqrt{P\dot{P}}$G from [10] we reach $\Delta P \sim 10^{-9}$ s for $m \approx 0.337$ GeV and $\Delta P \sim 10^{-13}$ s for $m \approx 0.354$ GeV, which can be measured experimentally.

For the same conditions, but for $m \approx 0.804$ GeV for $q_m = 2q_D$ we can estimate $\Delta B$ as $\sim$1 T and $\Delta P \sim 10^{-9}$ s. For $m \approx 0.819$ GeV for $q_m = 2q_D$ we have $\Delta B$ as $\sim$100 μT and $\Delta P \sim 10^{-13}$ s.

Very recent search for magnetic monopole production by the Schwinger mechanism in ultraperipheral Pb-Pb collisions at the Large Hadron Collider (MoEDAL) show that the monopole mass bound $m \ge 80$ GeV [28]. Magnetic monopoles with integer charges in the range between 2 and 45 Dirac units and masses up to 80 GeV were excluded by the analysis at the 95% confidence level.

Reference [28] contains Fig. 5, which shows the exclusion regions in the magnetic charge versus mass plane. The limit from indirect searches for magnetic monopoles produced by magnetars is also shown in Fig. 5 of [28].

Thus, in accordance with Ref. [28], for a monopole of mass $m \sim 82.2$ GeV (with $B \approx 5 \times 10^{11}$ T and with integer Dirac charges of 46), we can estimate $\Delta B$ as $\sim$100 μT and $\Delta P \sim 10^{-13}$ s.

If we take into account, that an inner magnetic field of magnetar may be as large as $10^{13}$ T [29], and the magnetic charge of the monopole is typically large $q_m = 46q_D$, for values $\Delta B \sim 10$ μT and $\Delta P \sim 10^{-13}$ s, which we still can potentially measure, we can detect magnetic monopoles with masses up to $m \sim 367.7$ GeV.

As we can see, all our estimations are in agreement with current limits for masses and charges of magnetic monopoles [28].

Thus, if magnetic monopoles with such masses and charges exist in nature, they may appear through magnetic monopole noise in the fluctuations in the spin period of magnetar.

Figure 1 shows the exclusion region in the magnetic charge versus mass plane.

## IV. RESULTS AND DISCUSSION

At the present moment 23 magnetars are known, with some more candidates awaiting confirmation [31]. Examples of known magnetars include SGR 0525-66, in the Large Magellanic Cloud, located about 163 000 light years from Earth, the first found (in 1979), and 1E 1048.1 −5937, located 9 000 light years away in the constellation Carina (it is also the closest magnetar to Earth), etc.

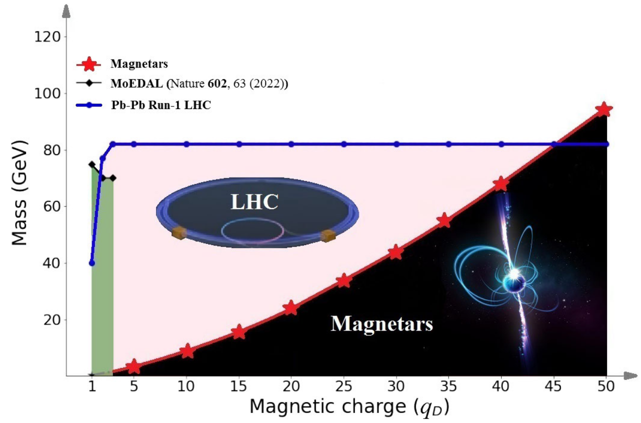


FIG. 1. The 95% exclusion region for magnetic monopoles production via the Schwinger effect in Pb–Pb collisions during Run-1 of the LHC [28]. The region shaded in green (online) corresponds to the mass bounds from the MoEDAL search [30]. The limit from indirect searches for magnetic monopoles produced by magnetars is also shown, indicating that the search [28] provides the strongest available limits for charges up to $45q_D$.

Magnetars are a type of neutron star, which is hard to study because they are far enough away from Earth.

The star's magnetic field can be determined by examination of the Zeeman effect lines. When the atoms in a star's atmosphere are within a magnetic field, characteristic dark absorption lines in the spectrum become split into multiple, closely spaced, lines.

However, it seems that this method is not sensitive enough for detection of the magnetic field fluctuations caused by the magnetic monopole noise.

Besides, in super strong fields, the coupling of orbital and spin moments is destroyed. As a result, the Zeeman effect of specific quasi-independent electrons has its place. Such fields strongly distort atoms, compressing atomic electron clouds into cigar shapes, with the long axis aligned with the field.

The effect of magnetic monopole noise is weak enough, and its presence in magnetar may be detected only by indirect methods.

Magnetic monopole noise leads to magnetic field fluctuations, which lead to spin period fluctuations of magnetar. In accordance with [28], for a monopole of mass m $\sim$ 82.2 GeV (with $B \approx 5 \times 10^{11}$ T and with integer Dirac charges of 46), we can estimate $\Delta B$ as $\sim$100 μT, and $\Delta P \sim 10^{-13}$ s. If we take into account that an inner magnetic field of magnetar may be as large as $10^{13}$ T [29] and the magnetic charge of the monopole is typically large $q_m = 46q_D$, for values $\Delta B \sim 10$ μT and $\Delta P \sim 10^{-13}$ s which we still can potentially measure, we can potentially detect, through fluctuations of period, magnetic monopoles with masses up to $m \sim 367.7$ GeV. For high masses of magnetic monopoles, $\Gamma$ decreases, respectively, the fluctuations of the magnetic field, and period fluctuations become smaller and go beyond the sensitivity of modern equipment.

In addition, magnetic monopole noise, for example, may be related to noise described in [32]. Magnetic field fluctuations may effect the magnetization of magnetar crust. Kondratyev in [32] assumed that the crust consists of nearly spherical nuclei with nucleus magnetic moments and considered the outer crust as polycrystalline structures with nuclei arranged in a close packed lattice. Such a system shows ferromagnetic ordering, and the crust can be viewed as a lattice of domains, each with its own magnetization. Thus, magnetic monopoles may effect the domains.

On the other hand, recent observations have revealed the existence of wind nebulae surrounding magnetars [33]. The difference between a magnetar wind nebula and a traditional pulsar wind nebula is that the magnetar wind nebula can be powered by the magnetic energy release [34]. The central magnetar's magnetic energy may first be converted to a system of particles (including magnetic monopoles). These particles will affect the radiation spectra of the magnetar, contributing a braking torque to the magnetar. When they flow out to the surroundings, they may be seen in the form of wind nebula. Thus, magnetic monopoles may interact directly with wind nebula particles.

Along with this, the nebula magnetic field may be related with the central magnetar's magnetic field [35]. Thus, magnetic field fluctuations, caused by magnetic monopole noise, through nebula magnetic field fluctuations may affect the particles of wind nebula.

In conclusion it is necessary to make some remarks about magnetic monopoles in general.

Roughly speaking, there are (hypothetically) two different types of magnetic monopoles: heavy and relatively light. Heavy monopoles, relic monopoles that formed very early in the Universe's history, which exist in grand unified theories (GUTs), have mass that is determined by the parameters of the theory, and in typical GUTs, it is very high, above $10^{16}$ GeV. GUT monopoles are far too massive to be produced in any present-day conditions in the Universe and in any of Earth's foreseeable accelerators.

In contrast, relatively light monopoles may be produced in the magnetic field of magnetars.

Why can we not observe magnetic monopoles in a cosmic ray?

This problem caused a lot of worry among the cosmologists around the world when it cropped up in the 1960s. Cosmologist Alan Guth [36] proposed a solution to this problem of magnetic monopoles. He proposed that the splitting of the GUT forces which could have caused the monopoles to plop into existence could also have caused them to become unobservable. This could have been possible due a rapid and massive expansion of the Universe caused by the energy released by GUT force split. The inflation of the Universe made it exponentially larger than what it was before inflation began. This means that the Universe is actually much larger than what we can observe. Therefore, it does not matter how many monopoles were created at the beginning of the Universe: the size of the Universe is extremely large, and therefore, when observed from Earth, we can only observe one magnetic monopole anywhere, a number which is too low to observe properly and a probable reason why we have still not observed monopoles.

But now there is the suggestion that the Amaterasu cosmic ray particle appears to have come from the direction of the local cosmic void and is a magnetic monopole rather than a proton or nucleus [37].

We can consider now the mechanism of interaction between two widely separated monopoles. If they are close enough to each other, the cores overlap, and we have quite a complicated picture of shortrange interactions mediated by the gauge and scalar fields. However, if we consider well separated monopoles, there is some simplification. We may suppose that the monopole core has a radius that is much smaller than the distance between the monopoles. Moreover, outside of this core the covariant derivatives of the scalar field vanish, and thus the gauge fields obey the free Yang–Mills equations. This approximation is a standard assumption in the analysis of monopole interactions. The results of both analytical and variational calculations confirm a conclusion, first observed by Manton [38]: there is no interaction between two Bogomol'nyi–Prasad–Sommerfield limit (BPS) monopoles at all, but the monopole-antimonopole pair attracts each other with double strength.

Monopole clusters are investigated, for example, in Abelian projected gauge theories [39]. But a discussion of these studies goes far beyond the scope of this article.

Let us now move to relatively light monopoles, which can be produced in the magnetic field of magnetar.

Each monopole accelerated toward the interstellar medium takes an energy from the magnetar magnetic field. The monopoles, which are accelerated toward the center of the star, either drift across it and escape by the opposite side or are trapped inside the star. If they escape by the opposite side, they will take the same amount of energy from the magnetic field, and if they are trapped, they will screen it. An alternative way of seeing this effect is to realize that the currents induced by the monopoles create a magnetic field opposite to that of the star.

Let us now consider the possibility that at least a few monopoles emitted in the interstellar medium interact with another magnetar of the Galaxy. The average distance between two magnetars is observed to be very large. The density of magnetars is expected to be relatively low (at the present moment 23 magnetars are known, with some more candidates awaiting confirmation). Such an interstellar monopole can be attracted by the magnetic field of a magnetar far away from it and funneled toward its surface. Thus, the monopoles will propagate from magnetar to magnetar, and in the timescale given by the size of the Galaxy, i.e., about $10^5$ years, all magnetars in the Galaxy will be demagnetized.

Magnetars can be observed, and their magnetic field and age can be estimated. The slowing down of magnetar rotation indicates a magnetic field strength of the order of $10^{15}$ Gauss. The active life of a magnetar is short compared to other celestial bodies. Their strong magnetic fields decay after about $10^4$ years, after which activity and strong x-ray emission cease. Thus, these rough estimations are not in contradiction with observations.

In any case, the density of magnetic monopoles (if they exist) in the interstellar medium is low. Besides, magnetic monopoles can interact with interstellar matter and be trapped in other cosmic objects.

## V. SUMMARY

The electromagnetic duality of Schwinger pair production provides a new way for understanding magnetic monopole production (generation). If monopoles exist, they would be produced in a sufficiently strong magnetic field of magnetars.

Our main conclusion is that the magnetic monopoles may play an important role in the reduction of magnetar magnetic fields, accompanied by magnetic monopole noise. Magnetic monopole noise leads to magnetic field fluctuations, which lead to spin period fluctuations of magnetar. Estimations show that such period fluctuations for the case of sufficiently light magnetic monopoles (if they exist) can be measured experimentally.

Thus, a new indirect method of detecting sufficiently light magnetic monopoles by the measurement of fluctuations in the spin period of magnetar is suggested.

If no fluctuations of the spin period are observed, this may mean that monopoles of a higher mass are produced in the magnetar field and the values of this fluctuations are beyond the sensitivity of modern equipment.

Besides, magnetic monopole noise may be related to magnetic noise in neutron star crusts or affected the particles of wind nebula surrounding magnetars.


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