Fast radio bursts could be triggered by gravitational perturbations in binaries

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Abstract

Observational evidence suggests that some repeating fast radio bursts (FRBs) should originate from magnetars in binary systems. In this study, we propose that the high burst rates observed in certain repeating fast radio bursts are caused by gravitational interactions between magnetars and their companion stars. These interactions perturb the internal velocity fields of these magnetars, thereby triggering episodic events such as glitches and X-ray bursts. Magnetic field variations associated with these episodic events can generate strong electric fields, accelerating charged particles and ultimately producing radio bursts. Within this framework of magnetic field variation, we propose a framework for understanding two fundamental issues of fast radio bursts, including both repeating and non-repeating fast radio bursts: how they are triggered, and how the charged particles responsible for coherent radio emission are accelerated.

Full Text

Fast radio bursts could be triggered by gravitational perturbations in binaries

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Observational evidence indicates that some repeating fast radio bursts (FRBs) should originate from magnetars in binary systems. In this study, we propose that the high burst rates observed in certain repeating FRBs result from gravitational interactions between magnetars and their companion stars. These interactions perturb the internal velocity fields of these magnetars, and then trigger sudden events such as glitches and X-ray bursts. The magnetic variations associated with these sudden events can induce strong electric fields capable of accelerating charged particles, ultimately producing radio bursts. Under this magnetic-variation frame, a way to understanding two fundamental questions about FRBs (both repeating and nonrepeating FRBs)—how they are triggered and how the charged particles responsible for coherent radio emission are accelerated—is presented.

I. INTRODUCTION

Fast radio bursts (FRBs) are intense and millisecond-duration radio emissions originating from the depths of the universe [1–5]. The vast majority of FRB samples are one-time events (may be temporarily), while others can burst repeatedly [6]. The association of FRB 20200428D and SGR 1935+2154 shows that, at least, a portion of FRBs can be attributed to magnetar activities [7–12]. However no observation reveal the specifics of these eruption processes. The physical origin of FRBs remain far from being fully elucidated. Different authors have attempted to understand these phenomena from various observational perspectives, such as the duration, luminosity, polarization, repeatability and periodicity [13–15]. In this study, we aim to identify common ground in the FRB triggering mechanism by analyzing the high burst rates observed in certain repeating FRB sources.

Recent observations of periodic variations in rotation measure and dispersion measure from several active repeating FRBs [16–19], along with periodic bursting patterns in two sources [20, 21], provide compelling evidences that these FRBs originate within binary systems. This presents a fundamental question: if magnetars are indeed the producers of all FRBs, why do those in binary systems appear preferentially capable of producing these bursts? This problem is intrinsically linked to the mechanism that triggers FRBs. To answer this question, in this study, we first examine the particular property of binary-system magnetars that may facilitate FRB production. We then argue how this special particularity enables more efficient burst generation. Finally, we generalize the proposed trigger mechanism to provide a unified framework that may explain both binary and non-binary FRB sources.

II. THE REASON OF HIGH BURST RATES

The direct difference between a magnetar in a binary system and an isolated magnetar is that the former has a companion star. Consequently, the high burst repetition rate of the magnetar in the binary system should be attributable to the companion. The companion can influence the magnetar through two primary ways: (a) matter exchange between the two objects; (b) gravitational interaction. If matter exchange is responsible for enhancing the burst rate, it would contradict observations that some repeating FRBs exhibit no significant RM variation (e.g., FRB 20180916B [22, 23] and FRB 20220912A [24])1. Thus, the second mechanism–gravitational interaction–is more likely the dominant driver of the elevated burst rate.

The gravitational interaction still has two ways to affect the magnetar. (i) The companion' s tidal force can deform the star. (ii) The companion' s gravity perturbs the velocity field of the magnetar' s internal superfluid. The first effect should be insufficient to trigger explosive energy releases (e.g., magnetar crust ruptures); otherwise, a pulsar in a close binary system would exhibit continuous quaking rather than a steady spindown (e.g., PSR 1913+16 [25])2. Thus, the plausible mechanism for enhancing the burst rate should be indirect gravitational influence–specifically, the modification of the magnetar' s internal velocity field. This raises another critical

1 Note that SGR 1935+2154 should be an isolated magnetar. This means that a magnetar can generate a FRB without the companion star' s matter exchanging.

2 This effect likely becomes significant only during the last inspiral phase, whether through gravity-induced crust ruptures or ruptures caused by star-deformation-driven magnetic variations [26]. If a crust rupture occurs, it could produce an electromagnetic precursor prior to the binary star merger.

question: how can changes in internal velocity fields of magnetars trigger FRBs?

A compelling analogy arises from observed associations between FRBs and phenomena such as X-ray bursts (XRBs) [9–12], glitches [27, 28], and antiglitches [29]. In these cases, magnetic variations are commonly confirmed [27, 30, 31] or invoked [32–35]. By extension, magnetic variations induced by changes in the velocity fields in magnetars should play a pivotal role in FRB generation. This speculation aligns with extensive observations of radio pulsars. The stability of radio pulses from Galactic pulsars in binary systems indicates that *shared properties between binary-system magnetars and other binary-system pulsars are only slightly perturbed during orbital motion*. The key distinguishing feature between a magnetar and an ordinary binary-system pulsar lies in the former' s significantly stronger magnetic field. Therefore, the influence of gravitational interactions on magnetic fields seems to be the only operative variable.

In summary, based on the preceding analysis, we claim that *the changes in the magnetar' s magnetic field induced by gravitational interaction between the magnetar and its companion star during the orbital motion are the reason for the high burst rates of the corresponding FRB*. This scenario requires magnetars in binary systems to exhibit greater magnetic-field susceptibility than other pulsars in similar binary configurations. XRBs of magnetars [36, 37] indeed show such a tendency. The natural follow-up question is: how do these magnetic variations induced by changes in velocity fields trigger FRBs?

III. THE TRIGGERS OF FRBS

FRBs are characterized by intense, short-duration energy releases. If the initial claim holds true, the variations in velocity fields, as well as magnetic fields, must be able to trigger abrupt energy releases (such as glitches and XRBs). Therefore, there must exist a critical threshold for the cumulative variations in velocity and magnetic fields. It is essential to determine whether the changes induced by gravitational perturbations can reach this threshold and trigger such abrupt events. Given that pulsar activities are primarily driven by spindowns, we next examine variations in spin periods.

As shown in Figure 1, a charged fluid element within the magnetar undergoes acceleration and deceleration in the gravitational field of the companion star as the magnetar rotates. The gravitational force experienced by the magnetar depends on the distance, d, between the magnetar and the companion star. The semimajor axis, a, of the elliptical orbit is

$$\begin{aligned} a &= \left[\frac{T^2}{4\pi^2} G(M_{\rm c}+M_{\rm m})\right]^{1/3} \\ &= 1.4\times 10^{13}\ {\rm cm}\left(\frac{T}{100{\rm day}}\right)^{2/3}\left(\frac{M_{\rm c}+M_{\rm m}}{10M_{\odot}}\right)^{1/3}, \end{aligned} \tag{1}$$

FIG. 1. A charged fluid element (Δm) within a magnetar undergoes acceleration and deceleration in the companion's gravitational field ($F_{\rm g}$) as the magnetar rotates (the spin Ω), where u is the velocity of the material co-orbiting with the neutron star relative to the background charge field.

where T is the orbital period, G is the gravitational constant, $M_{\rm c}$ is the mass of the companion star, and $M_{\rm m}$ is the mass of the magnetar (maybe a Be star [39]). The total gravitational potential energy that can be used to perturb the velocity field in the magnetar is

$$\begin{aligned} \Delta E_{\rm p} &\approx \int_V \frac{GM_{\rm c}}{2d^2}\cdot \rho(r) r^3 \sin\theta\, dr\, d\theta\, d\varphi \\ &= \frac{3\pi(GM_{\rm c}M_{\rm m}R_*)}{8d^2} \\ &= 1.9\times 10^{40}\ {\rm erg}\left(\frac{M_{\rm c}}{8.6M_{\odot}}\right)\left(\frac{M_{\rm m}}{1.4M_{\odot}}\right) \\ &\quad \times\left(\frac{R_*}{10^6{\rm cm}}\right)\left(\frac{d}{1.4\times 10^{13}{\rm cm}}\right)^{-2}, \end{aligned} \tag{2}$$

where V is the volume of that half of the magnetar which is oriented away from its companion star, R_* is the star radius, and a uniform mass density, ρ, is adopted. Therefore, the average change in the spin period, $\overline{\Delta P}$, is

$$\begin{aligned} \overline{\Delta P} &= \frac{\Delta E_{\rm p} P^3}{4\pi^2 I} \\ &= 2.5\times 10^{-4}{\rm s}\left(\frac{\Delta E_{\rm p}}{10^{40}{\rm erg}}\right)\left(\frac{P}{10{\rm s}}\right)^3\left(\frac{I}{10^{45}{\rm g\ cm^2}}\right)^{-1} \end{aligned} \tag{3}$$

where P is the spin period and I is the rotational inertia. Note that the value of the change in the spin period, ΔP, is a function of (r, θ, φ).

As a comparison, the change in the spin period required for triggering glitches or XRBs[3] is

$$\dot{P}\Delta t = 3.2 \times 10^{-4}\mathrm{s}\left(\frac{\dot{P}}{10^{-11}\mathrm{s\ s^{-1}}}\right)\left(\frac{\Delta t}{1\mathrm{yr}}\right), \quad (4)$$

[3] Note that magnetar glitches are typically associated with XRBs [38].

where $\dot{P}$ is the spin-down rate[1], and Δt is the time interval between two glitches or two active phases of XRBs. By comparing Equations (3) and (4), one can find that the gravitational interaction-induced variations may achieve the threshold magnitude required to trigger glitches or XRBs.

When a glitch or an XRB is triggered, the magnetic field may concomitantly undergo a significant change, with the variation, $\Delta B'$, reaching a magnitude comparable to the strength of the magnetic field itself, as shown by observations [27, 30, 31] and theoretical models [32, 35]. For example, since the internal magnetic field is coupled with the internal velocity field in the magnetar, variations in the velocity field will induce changes in the magnetic field, as well as the release of magnetic free energy. Under the linear perturbation of the induction equation, the magnetic variation accompanied by the release of magnetic free energy induced by the perturbation of the velocity field can be approximated up to (see Appendix A)

$$\begin{aligned}\Delta B &= \frac{\Delta P_{\mathrm{max}}}{P}B_0 \\ &= 1.0 \times 10^{12}\,\mathrm{G}\left(\frac{\Delta P_{\mathrm{max}}/P}{10^{-4}}\right)\left(\frac{B_0}{10^{16}\,\mathrm{G}}\right),\end{aligned} \quad (5)$$

where B_0 is the internal magnetic-field strength of the magnetar, and ΔP_{max} is the largest value of the change in the spin period. The typical value given by Equation (5) is consistent with the typical value of the magnetic variation required by crust fractures that [32, 41]

$$\begin{aligned}\Delta B_c &\sim \frac{4\pi u\theta_{\mathrm{max}}}{B_0} \\ &= 1.2 \times 10^{12}\,\mathrm{G}\left(\frac{u}{10^{30}\,\mathrm{dyn\,cm^{-2}}}\right) \\ &\quad \times \left(\frac{\theta_{\mathrm{max}}}{10^{-3}}\right)\left(\frac{B_0}{10^{16}\,\mathrm{G}}\right)^{-1},\end{aligned} \quad (6)$$

where u is the shear modulus, and θ_{max} is the breaking strain. When the crust breaks off, the fractured crust will carry the anchored magnetic field lines on it to slide on the magnetar surface. This motion can significantly alter the local magnetic-field configuration. The sudden magnetic variation on the magnetar surface will induce an electric field, which can be up to

[1] https://www.atnf.csiro.au/research/pulsar/psrcat/ [40].

$$
\begin{aligned}
E_i &= \left| -\frac{\Omega \times r \times \Delta B'}{c} \right| \\
&= 2.1 \times 10^9\,\mathrm{V\,cm^{-1}} \left(\frac{P}{10\,\mathrm{s}}\right)^{-1} \left(\frac{r\sin\theta}{1\,\mathrm{km}}\right) \left(\frac{\Delta B'}{10^{15}\,\mathrm{G}}\right).
\end{aligned}
\tag{7}
$$

For curved magnetic field lines with a radius of curvature typically being $\sim R_*$, the electric potential along these field lines can be $\sim E_i R_* \sim 10^{15}\,\mathrm{V}$. It seems that $E_i R_* \sim 10^{15}\,\mathrm{V}$ appears significantly larger than the usually invoked value for generating periodic radio pulses (e.g., $\sim 10^{12}\,\mathrm{V}$; see the inner gap model [45]), so that $E_i R_*$ cannot be up to $\sim 10^{15}\,\mathrm{V}$ due to screening by charged particles produced in sparks. However, unlike the electric field in the inner gap whose strength scales with gap height, the electric field induced by the magnetic variation can instantaneously appear in the region where such variation occurs. Therefore, $E_i R_* \sim 10^{15}\,\mathrm{V}$ is realistic. This is also consistent with the common opinion that the electromotive force from unipolar induction acts as the "supply voltage" of a pulsar. Once the induced electric field appears, it generates a far greater number of charged particles than the electric field typically invoked in the inner gap ($\sim 10^{15}/10^{12} = 10^3$ times). Consequently, if the charged particles accelerated by the induced electric field can also generate coherent radio emission just like the particles responsible for periodic radio pulses[2], the brightness temperature of this emission could be $\sim (10^{15}/10^{12})^2$ times that of the periodic radio pulses, i.e., $\sim 10^{36}\,\mathrm{K}$, which is consistent with the typical brightness temperature of FRBs [15].

Under the above scenario, a glitch or an XRB can be accompanied by a burst of a repeating FRB sequence. Therefore, the typical burst rate can be up to $\sim 360(P/10\,\mathrm{s})^{-1}\,\mathrm{hr}^{-1}$, which significantly alleviates the challenges in understanding high burst-rate phenomena [46, 47].

IV. SUMMARY AND DISCUSSION

Building on an FRB-XRB association and certain periodicity revealed by some observations, we show that if a repeating FRB with a high burst rate originates from the magnetar in a binary system, the elevated burst rate can be explained by the gravitational interaction between the magnetar and its companion star. The gravitational interaction perturbs the internal velocity field of the magnetar, and the accumulated variation in the internal velocity field of the magnetar ultimately induces a sudden event, such as a glitch or an XRB. The strong magnetic change associated with the sudden event will generate a strong electric field. If the charged particles accelerated by this electric field can produce coherent radio emission akin to the emission generated by the particles responsible for

[2] Coherent radio emission generated in the open field line region may be preferred [42, 43]. However, a powerful outflow could also clear a pathway in the closed field line region for FRB emission [29], so that the puzzle concerning the absence of detected magnetar spin periods in FRB observations would be relieved.

periodic radio pulses, the resulting event may manifest as a single burst within a repeating FRB sequence.

Under the trigger scenario presented in this study, magnetic free energy provides the energy required by an FRB. The critical magnetic variation determined by equation (6) constrains normal pulsars as possible sources of FRBs. In other words, a radio burst can be produced as long as evident magnetic evolution occurs (e.g., magnetic variations resulting from spin-down- or accretion-induced crustal fractures), so that a single magnetar could serve as the source of a repeating FRB with a relatively low burst rate. A possible example consistent with this idea is FRB 20200428D (and FRB 20171019 may also be such a case [48–51]). According to the X-ray observations of SGR 1935+2154 [7–12], it is conjectured that the persistent release of magnetic free energy via XRBs leads to internal magnetic-field decay in the magnetar; such magnetic decay ultimately induces the Rayleigh–Taylor instability and magnetic-field reconfiguration [32], and then results in a stronger magnetic variation that meets the condition for the generation of a radio burst.

Appendix A

Due to this extra gravitational field, the velocity of the fluid element changes as $\mathbf{u}_0 \to \mathbf{u} = \mathbf{u}_0 + \Delta\mathbf{u}$. Accordingly, the magnetic field will be $\mathbf{B}_0 \to \mathbf{B} = \mathbf{B}_0 + \Delta\mathbf{B}$. According to the induction equation over a short duration (e.g., one period),

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}), \tag{A1}$$

and given $\mathbf{B}_0$ and $\mathbf{u}_0$, which satisfy

$$\frac{\partial \mathbf{B}_0}{\partial t} = \nabla \times (\mathbf{u}_0 \times \mathbf{B}_0) \approx 0, \tag{A2}$$

we begin with the following simplified equation, which serves as the initial step in solving Equation (4) using the iterative method:

$$\frac{\partial \Delta\mathbf{B}}{\partial t} = \nabla \times (\Delta\mathbf{u} \times \mathbf{B}_0). \tag{A3}$$

Since the orbital radius is much larger than the radius of the magnetar, in the spherical coordinate frame shown in FIG. 1, the velocity variation can be approximately taken as $\Delta\mathbf{u} = (0, 0, \Delta u(r, \theta, \varphi))$. Then, equation (A3) gives

$$\frac{\partial \Delta B_r}{\partial t} = -\frac{1}{r \sin\theta} \frac{\partial}{\partial \varphi} (\Delta u B_{0,r}), \tag{A4}$$

$$\frac{\partial \Delta B_\theta}{\partial t} = -\frac{1}{r \sin\theta} \frac{\partial}{\partial \varphi} (\Delta u B_{0,\theta}), \tag{A5}$$

and

$$\frac{\partial \Delta B_{\varphi}}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(r\Delta u B_{0,r}) + \frac{1}{r}\frac{\partial}{\partial \theta}(\Delta u B_{0,\theta}). \tag{A6}$$

The perturbation in the velocity of the charged fluid element arises from gravitational interaction; it follows that $\Delta u = -\Delta\omega(r,\theta,\varphi) r \sin\theta$, where $\Delta\omega$ is the perturbation of the angular velocity of the charged fluid element, and the minus sign comes from the condition that the magnetic field in the polar-cap region of the magnetar is antiparallel to the angular velocity. On the other hand, the velocity variation of the fluid element exhibits periodicity (the variation of ΔE_p over a spin period is negligible compared to its own magnitude), so $\Delta\omega$ can be roughly given by its dominant Fourier component, yielding $\Delta\omega \approx C(r,\theta)\sin(\varphi/2) \approx C\sin(\Omega_0 t/2)$, where Ω_0 is the spin at the initial time of the perturbation (at point X). Assuming an axisymmetric field $\mathbf{B}_0 = \mathbf{B}_0(r,\theta)$, equation (A4) gives

$$\Delta B_r = \frac{C B_{0,r}}{\Omega_0}\sin(\Omega_0 t/2), \tag{A7}$$

and equation (A5) gives

$$\Delta B_{\theta} = \frac{C B_{0,\theta}}{\Omega_0}\sin(\Omega_0 t/2). \tag{A8}$$

Since $\mathbf{B}_0 = \mathbf{B}_0(r,\theta)$ is unknown, it is hard to obtain useful information about the toroidal component from equation (A6). However, according to the energy-conservation law, equation (A6) implies that the release of magnetic free energy stored in the toroidal component enhances the strength of the poloidal component. Substituting $C \approx -\frac{2\pi}{P^2}\Delta P$ into equation (A7) or (A8), we obtain equation (5), where ΔP is the variation in the spin period.

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