ESCAPE OF FAST RADIO BURSTS FROM MAGNETARS’ MAGNETOSPHERES

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ABSTRACT

We discuss dissipative processes occurring during production and escape of Fast Radio Bursts (FRBs) from magnetars’ magnetospheres, the presumed loci of FRBs. High magnetic field is required in the emission region, both to account for the overall energetics of FRBs, and in order to suppress “normal” (non-coherent) radiative losses of radio emitting particles; this limits the emission radii to \( \lesssim \text{few} \times 10 R_{\text{NS}} \). Radiative losses by particles in the strong FRB pulse may occur in the outer regions of the magnetosphere for longer rotation periods, \( P \geq 1 \) second. These losses are suppressed by several effects: (i) the ponderomotive pre-acceleration of background plasma along the direction of wave propagation (losses reduced approximately as \( \gamma^3 \); smaller frequency, \( \propto \gamma^2 \) in power, and times scales stretched, \( \propto \gamma \)); this acceleration is non-dissipative and is reversed on the declining part of the pulse; (ii) Landau-Pomeranchuk-Migdal effects (long radiation formation length and ensuing destructive interference of scattered waves). In some cases an FRB pulse may be dissipated on external perturbations (e.g. an incoming pulse of Alfvén waves): this may produce a pulse of UV/soft X-rays possibly detectable by Chandra.

Three principal factors contribute to the suppression of the “normal” losses in magnetar magnetospheres: (i) high magnetic field, (ii) relativistic outward motion of plasma; (iii) destructive interference of waves scattered by plasma particles. In the highly guide-field dominated regime, when cyclotron frequency is much larger than the wave frequency, the parameter \( a \) loses its importance. The high magnetic field in the inner regions of the magnetosphere modifies particle motion in the coherent wave: instead of experiencing acceleration on the time scale of quarter of a period \( \sim 1/\omega \), the magnetic field bends particle trajectory on time scale \( \sim 1/\omega_B < 1/\omega \) (Lyutikov et al. 2016; Lyutikov 2020, 2021a).

As Lyutikov & Rafat (2019) argued, in the absence of strong guide-field a coherently emitting particle will lose energy on time scales shorter than the coherent low frequency wave. Thus large magnetic field are required in the emission region. Particles that produce coherent EM waves in the inner parts of the magnetosphere do not suffer “normal” (non-coherent) losses due to the high magnetic field. But these losses may become important in the outer regions of the magnetosphere.

Beloborodov (2021) argued that losses in the outer parts of the magnetosphere will prevent escape of radio waves. Beloborodov (2021) argued that the combined effects of enhanced scattering cross-section, and what we call the “normal losses” would lead to strong energy dissipation of the wave. In this contribution we show that, first, in the outer regions of the magnetars’ magnetospheres FRBs induce, via ponderomotive force, large Lorentz factor motion parallel to the direction of wave propagation. As a result, the corresponding self-losses are negligible. Losses in the external fields (e.g. the background magnetic field and/or Alfvén wave propagating through the magnetosphere) may occasionally be important and may lead to observable effects.

1. INTRODUCTION

Observations of correlated radio and X-ray bursts [CHIME/FRB Collaboration et al. 2020; Kidswa et al. 2021; Bochenek et al. 2020; Mereghetti et al. 2020; Li et al. 2021] established the FRB-magnetar connection. Temporal coincidence between the radio and X-ray profiles, down to milliseconds, argues in favor of magnetospheric origin [Lyutikov & Popov 2020]: we know that X-ray are magnetospheric events, as demonstrated by the periodic oscillations seen in giant flares [Palmer et al. 2003; Hurley et al. 2005]. Also, the fact that radio peaks lead the X-rays (Mereghetti et al. 2020) is consistent with the prediction that acceleration occurs at the initial stage of the reconnection event, while the surrounding plasma is relatively clean of the pairs [Lyutikov & Rafat 2019].

Lyutikov et al. (2016); Lyutikov & Rafat (2019) discussed the overall constraint that observations impose on the FRB loci (this includes the required plasma density, magnetic field and bulk motion). They concluded that magnetars generally satisfy those constraint.

The magnetic field plays the most important role in the generation and propagation regions. At the core of it is the laser non-linearity parameter [Akhiezer et al. 1973]:

\[
a \equiv \frac{cE_w}{m_e c \omega}
\]

where \( E_w \) is the electric field in the coherent wave, and \( \omega \) is the frequency (parameter \( a \) is Lorentz invariant). In FRBs its value can be as large as \( \sim 10^6 \) [Luan & Goldreich 2014; Lyutikov et al. 2016]. In unmagnetized plasma the nonlinearity parameter \( a \) is a dimensionless momentum of transverse motion of a particle in the EM wave. As a result, particles moving with Lorentz factor \( \gamma = a \) in the electromagnetic experience “normal” losses (this is a radiation reaction effect and is usually not taken into account).

2. OVERALL ENERGETICS

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Let’s normalize the surface magnetic field to the quantum field

\[
B_{NS} = b_q B \quad \text{and} \quad B = \frac{c^3 m_e^2}{e h}
\]

Then the energy needed to power the radio burst is contained within

\[
R_f = \left( \frac{24 \pi D^2 \nu F_{\nu} \tau}{B_{NS}^2} \right)^{1/3} = 1.5 \times 10^4 \times b_q^{-2/3} \text{ cm},
\]

about a football field.

Alternatively, assume that the total duration of the burst is due to "lateral" extension of an active region located near the neutron star surface, as its direction of emission swings by an observer:

\[
R_f = \frac{\tau}{P} R_{NS}
\]

where \( P \) is the rotation period. Emission is then confined into solid angle \( \pi \theta_0^2, \theta_0 = (R_f/R_{NS}) \). The real energetics is \( \pi (\tau/P)^2 \) smaller,

\[
E_{\text{real}} = 4 \pi^2 D^2 \nu F_{\nu} \tau^3 \frac{P}{P} = 3 \times 10^{33} P^{-2} \text{ erg}
\]

for period measured in seconds. Such amount of energy is contained within the layer of thickness

\[
\frac{(\Delta R)}{R_{NS}} = \frac{32 \pi^2 D^2 \nu F_{\nu} \tau}{b_q^2 B_{Q}^2 R_{NS}^2} = 1.5 \times 10^{-5} b_q^{-2}
\]

about 15 centimeters only.

Radio emission is a tiny fraction of the total energy budget - mostly the energy is spent on the accompanying X-ray emission [Ridnaia et al. 2021, Bochenek et al. 2020, Mereghetti et al. 2020], and presumably ejection of a plasma from the magnetosphere. Relation (7) demonstrates that X-ray power exceeding the radio by \( 10^9 \) can be accommodated within the magnetospheric model.

3. ESCAPE OF FBRS FROM MAGNETARS’ MAGNETOSPHERES

3.1. Lorentz transformations

Consider an emission region moving with Doppler factor \( \delta \). Let’s denote the quantities measured in the plasma frame with primes. The Lorentz transformations of frequency, flux, brightness temperature, radiation energy density and duration read [Ghisellini 2013, Lyutikov & Rafat 2019]

\[
\nu' = \nu / \delta \quad F'_{\nu'} = F_{\nu} / \delta^3 \quad T'_b = T_b / \delta^3 \quad u'_{\text{rad}} = u_{\text{rad}} / \delta^4 \quad \tau' = \tau \delta
\]

In the generation region the energy density of plasma particles \( u'_p \) should exceed the energy density of radiation \( u'_{\text{rad}} \) (particles cannot emit more energy than they have). In addition, in magnetar magnetospheres we expect that the energy density is dominated by the energy density of the magnetic field \( u_B \). Thus,

\[
u'_p \geq u'_p \geq u'_{\text{rad}}
\]

Let us consider two case, first, when the emission region is scaled with the (Lorentz-boosted) total duration of the burst, (32) and, second, when duration is determined the lateral extension of an active region near the surface of a rotating neutron star (3.3).

3.2. Size of emission region scaled \( \propto \tau c \)

Given the observed flux \( F_{\nu} \), duration \( \tau \) and distance to the source \( D \), radiation energy densities evaluate to

\[
u_{\text{rad}} = \frac{D^2 \nu F_{\nu}}{c^2 \nu^2}
\]

and \( u'_p \) is expressed in terms of the observed quantities.

Requirement \( u'_p \geq u'_{\text{rad}} \) gives the estimate of the magnetic field (a limit from below):

\[
u_{\text{eq}} \geq 2 \sqrt{\frac{F_{\nu} \delta D}{\tau c^3/2}} = 2 \times 10^8 \times \delta^{-2} G
\]

For surface magnetic field parametrized as (3) this is satisfied for

\[
\frac{r_{\text{em}}}{R_{NS}} \leq \frac{b_q^{1/3} D Q^{1/3} \sqrt{c^1/3}}{2^{1/3} \pi^{1/6} (F_{\nu} \nu)^{1/6} D^{1/3}} \delta^{2/3} = 60 \times b_q^{1/3} \delta^{2/3}
\]

Thus, emission must be produced in the inner parts of the magnetosphere.

If FRBs are produced during magnetic reconnection events, one might expect that in the dissipation region \( u_B \sim u_p \). If the energy density in particle is smaller than in magnetic field, \( u_B = \sigma u_p, \sigma \geq 1 \), all the relation below will be modified as \( b_q \rightarrow \sigma^{-1/2} b_q \). For example, condition (12) becomes

\[
\frac{r_{\text{em}}}{R_{NS}} \leq \frac{b_q^{1/3} D Q^{1/3} \sqrt{c^1/3}}{2^{1/3} \pi^{1/6} \sigma^{1/6} (F_{\nu} \nu)^{1/6} D^{1/3}} \delta^{2/3} \sigma^{-1/6}
\]

In what follows we omit the factor \( \sigma \), with understanding that \( b_q \equiv \sigma^{-1/2} \).
momentum of a particle in the electromagnetic wave, \( a \sim p_L/(m_ec) \). If a particle oscillates in the electromagnetic fields of the coherent wave with amplitude \( a \), then in addition to the energy losses to the emission of coherent waves it will also suffer Inverse Compton (IC) and synchrotron losses (if magnetic field is present). Those “normal” losses will dominate over the “coherent” losses.

The normal loss time scale can be estimated as \( \tau_{loss} \):

\[
\frac{\gamma' m_ec^2}{\tau_{loss}} = \frac{e^6 u_{rad} \gamma'^2}{m^2 c^5}
\]

\[
\tau_{loss} = \delta \tau'_{loss} \quad (15)
\]

(We use energy loss estimate in turbulent radiation field parametrized by energy density \( u_{rad} \), not in a single coherent wave, Eq. (24). This is more appropriate in the wave production region.)

We find

\[
\frac{\tau_{loss}}{\tau} = \sqrt{\pi} \frac{c^{21/2} m^4 \nu^2}{e^6 F_\nu B_\nu^{1/2} \nu^{1/2} D^3} \delta^6 = 10^{-10} \delta^6 \quad (16)
\]

Thus, in the absence of guiding magnetic field normal losses will drain particles’ energy before it has time to emit a coherent wave.

Lyutikov & Rafat (2019) formulated the corresponding condition in terms of the effective brightness temperature \( T_b \). The synchrotron/IC radiation decay times become shorter than pulse duration for

\[
T_b \geq \frac{1}{k_B} \frac{m_e^{8/3} c^7}{e^{10/3} \nu^{2/3} \gamma'^2} = 10^{29} \text{ K}
\]

\[
T_b = \left( \frac{\lambda}{\nu B_\nu} \right) T_{b,0} \quad (17)
\]

\( T_b \) incorporates finite spectral bandwidth and anisotropy of the emission; \( T_{b,0} \) is the observed brightness temperature. \)

There is an important caveat to the above statements, which resolves the problem of large normal losses in the FRB production region Lyutikov et al. 2016 Lyutikov & Rafat (2019). In the limit of large guiding magnetic fields, with \( \omega_D \geq 2\pi \nu' \) where \( \omega_D = eB_\nu/(m_ec) \) and \( \nu' \) is the wave frequency in the source frame, the nature of the particle’s motion in the field of the electromagnetic wave changes: instead of oscillations in the electric field of the wave with the dimensionless momentum \( a \), a particle experiences slow drift with velocity \( v_d/c \sim E'/B_0 \) (here \( E' \) is the electric field of the wave, while \( B_0 \) is the external magnetic field). This condition translates to

\[
B_0 \geq \frac{m_ec^2}{e\lambda \delta} \approx 100\delta^{-1} \text{ G} \quad (18)
\]

Thus, the presence of high magnetic fields in high brightness relativistic sources is required to avoid large radiative losses of coherently emitting particles to IC and synchrotron processes.

3.3. Size of emission region \( \propto (\tau/P) R_{NS} \)

Repeating estimates of the 3.2 we find

\[
u_{rad} = \frac{D^2 \nu F_\nu}{eF_{NS}^2}
\]

\[
B_{eq} = 2\sqrt{2\pi} (\nu F_\nu)^{1/2} D \sqrt{\epsilon R_{NS}} = 8.6 \times 10^{9}\text{G}
\]

\[
r_{em} \leq \frac{b_{1/3} B_{q}^{1/3}}{2^{1/2} \pi^{1/6} (F_\nu \nu)^{1/6} D^{1/3}} = 17 b_{q}^{1/3} \quad (19)
\]

A very much similar result.

3.4. Losses in the escape region

3.4.1. Intrinsic losses in the field of FRB pulse

As an FRB pulse propagates away from the star, the guiding field decreases. At distances larger than \( r_{em} \) the electromagnetic fields in the wave are larger than the guiding field. This does not lead to dissipative effects, since the particle motion in the wave still occurs on fast time scale given by the guide field - particles do not have time to acquire large energy from the electric field of the wave.

For a given surface field the condition \( \omega \leq \omega_B \) (18) implies radii

\[
r_{r, \nu} \leq \frac{b_{1/3} (eB_\nu/m_e \omega)}{17 b_{q}^{1/3}} \quad (20)
\]

Condition \( r_r \equiv R_{LC} \) (light cylinder radius) is achieved for periods of

\[
P_r = \left( \frac{4\pi^2 b_\nu B_\nu}{m_e c \nu} \right)^{1/3} \approx 1\text{s} \quad (21)
\]

For neutron stars with shorter period, \( P \leq P_r \), the frequency of the waves is \( \omega \leq \omega_B \) everywhere in the magnetosphere: EM wave-particle interaction is then suppressed everywhere within the magnetosphere.

Let us next consider slower neutron stars, \( P \geq P_r \). In the outer regions of the magnetosphere \( \omega \leq \omega_B \): this is the conventional laser-plasma interaction regime where guide field is not important.

As the waves propagate from their origin near the neutron star, their amplitude decreases as \( 1/r \). At the radius \( r_r \), we have

\[
a_r = \frac{e\nu D/T_{r_\nu}}{\sqrt{\pi m_e c^{3/2} r_r \nu}} \approx 3.5 \times 10^5 b_{q}^{-1/3} \quad (22)
\]

Let us first consider single particles losses in an electromagnetic with amplitude (22) (collective effects are discussed in (11)). Importantly, as the FRB pulse propagates through the magnetosphere particles experience ponderomotive force that accelerates them along the direction of the wave propagation to \( \gamma_{||} = \sqrt{1 + a^2} \approx a \) Sprangle et al. (1991). (A simple way to see this is to consider FRB pulse as a packet of highly relativistic, nearly luminal Alfvén waves. Total energy is then conserved, transverse Lorentz factor is of the order of the parallel one). This is a non-dissipative process: the particle will give all the parallel energy back to the pulse on the descending part of the intensity envelope.

Acceleration to \( \gamma_{||} = a \) assumes pulse propagation parallel to the external magnetic field. For propagation perpendicular to the external field both the particles and the fields will be accelerated Beloborodov (2021), but since ponderomotive force acts on time scales much longer that the cyclotron gyration in the dipolar field,
no cyclotron motion will be excited (adiabatic process - no Landau transitions): no dissipation, energy exchange between FRB pulse and plasma is reversible. Also, the energy of the dipolar magnetic field within a volume of a pulse at \( r \), is much smaller than the energy of the pulse, \( 4\pi r_c^2 (c/\tau_r)^2 B^2 / (8\pi) / E_{\text{iso}} = 4 \times 10^{-8} \) - plasma will be accelerated to \( \gamma \gg 1 \) in this case as well.

In the frame of the particle the losses are controlled by

\[
\begin{align*}
\gamma' m_e c^2 / \tau_{\text{loss}} &= \varepsilon \gamma^4 \omega_p^2 \quad (23) \\
\gamma' &\sim a \\
\tau_{\text{loss}} &= \frac{m_e c^3}{a^2 \varepsilon \omega_p^2} \quad (24)
\end{align*}
\]

(the coefficient on the rhs of (23) is 2/3 for circularly polarized wave and 1/8 for linearly polarized Landau & Lifshitz 1975).

In the lab frame

\[
\tau_{\text{loss}} = \delta \tau_{\text{loss}} = \frac{8 m_e c^3}{a^2 \varepsilon \omega_p^2} = 2 \times 10^4 \text{ seconds} \quad (25)
\]

where we used \( \delta = 2a \) - this is the effect of the ponderomotive acceleration. Qualitatively, bulk ponderomotive acceleration “kills” all the losses approximately as \( \gamma_3^3 \): smaller frequency (\( \propto \gamma^2 \) in power), and times scales stretched (\( \propto \gamma \)). It is remarkable that the time scale (25) is independent of the pulse intensity parameter \( a \).

The loss time scale (25) is very long, much longer than the expected period of a magnetar: FRB pulses do not suffer from strong radiative self-damping in the outer parts of the magnetar’s magnetospheres.

3.4.2. External losses

More dangerous are “external” losses: particles moving relativistically in the EM field of the FRB pulse with the total Lorentz factor \( \gamma \sim a_0^2 \sim 10^7 \) (a product of parallel ponderomotively induced and perpendicular Lorentz factors) may also lose energy due to radiative process not intrinsic to the pulse, but external magnetoospheric perturbations. If the energy density of external perturbations in the lab frame is \( u_{\text{ex}} \), the corresponding loss rate would be

\[
\tau_{\text{loss,ex}} = \frac{m_e^2 \varepsilon^5}{a_0^2 \varepsilon^3 u_{\text{ex}}} \quad (26)
\]

where the intensity parameter \( a_0 \) is given by (22).

Various estimates can be made to estimate \( u_{\text{ex}} \). For example, if both the liner and the oscillating momenta of the particles induced by the FRB wave are mostly perpendicular to the underlying magnetic field, the synchrotron loss time scale with \( u_{\text{ex}} = B^2 / (8\pi) \), is \( \tau_{\text{loss,ex}} \sim 10^{-2} \) seconds - it may be important. (The corresponding photon energy is \( \sim 500 \text{ MeV} \). This extreme case demonstrates that external (to the proper FRB wave) effects may lead to the dissipation of the FRB energy. But they do not have to.

Another possibility is if a beam of leptons accelerated by the FRB pulse encounters Alfven wave with the wavelength \( \lambda_A \) (somewhat) shorter that \( r_r \), \( \lambda_A = \eta_A r_r \), \( \eta_A \ll 1 \). For \( \eta_A = 10^{-2} \), this will produce a UV/soft X-ray pulse with the same power as the FRB proper, a “swan song” of an FRB. The corresponding peak flux

\[
F = \frac{\nu F_{\nu} \lambda_{\nu}}{h \nu} = 10^{-4} \text{phot cm}^{-2} \text{s}^{-1} = 2 \times 10^{-16} \text{erg cm}^{-2} \text{s}^{-1} \quad (27)
\]

\( \omega_A = 2\pi c/\lambda_A \), could in principle be detected with sensitive instruments like Chandra’s High Resolution Camera. The peak flux (27) lasts only a millisecond (for other estimates of FRBs’ signals see Lyutikov & Lorimer 2010).

4. Further suppression of losses due to LPM effect.

Finally let us comment on the very applicability of a single particle approach in calculating radiative losses in a strong electromagnetic wave. In the absence of the guide field the single particle scattering cross-section in a strong wave with \( a \gg 1 \) is enhanced (non-linear Thomson scattering, Zeldovich 1973 Esarey et al. 1993).

\[
\sigma = \sigma_T (1 + a_r^2) \quad (28)
\]

(or by \( (1 + a_r^2 / 2 \) for linearly polarized wave). (Non-linear Thomson scattering in the guide-field dominated regime has been considered by Lyutikov 2021).

Importantly, the criterium for the single particle interaction (versus collective) is that the radiation formation length is smaller than the distance between particles. Even though high energy particle emit short wavelength \( \lambda_{\text{em}} = c/\omega_{\text{em}} \) the radiation formation length is long \( l_c \sim \gamma^2 \lambda_{\text{em}} \), Fig. ?? ??.. This surprising result (first discussed in applications to high energy particle scatterings) is known as the Landau-Pomeranchuk-Migdal (LPM) effect Migdal 1956, also discussed by Ter-Mikaelian 1961, Lyutikov 2021).

In the case of motion in circularly polarized wave a particle rotates with radius \( c/\omega' \), where \( \omega' \) is the frequency of the wave in the frame where the particle is at rest on average (guiding center frame). At each moment the magnetic field of the wave is counter aligned with the velocity while the electric field provides the centrifugal force. Single particle emitted frequency is \( \sim a_0 \omega' \), while the radiation formation length is \( l_c \sim (c/\omega') / a_0 \). If inter-particle distance is smaller than \( l_c \) inference of waves emitted by different particles will reduce the intensity of the scattered waves. In the continuous limit the emission is suppressed completely: a ringing current does not emit.

In the frame of the ponderomotively accelerated plasma \( \omega' = \omega / a_0 \), hence \( l_c \sim c / \omega \). Since this is the length along particle motion, hence across wave propagation direction, it is the same in the lab frame, \( l_c = l_c \sim c / \omega \). It will be typically larger than the inter-particle distance.

Thus, in the continuous limit the enhanced cross-section for the non-linear Thomson scattering does not lead to any losses, no extra scattering opacity. In this case the waves scattered from different particles add constructively along the direction of wave propagation. Just as in the conventional cold plasma, in the continuous regime Thomson scattering by individual electrons leads only to the modification of the dispersion relation. In the non-linear regime, for circularly polarized light the photon dispersion becomes (Akhiezer et al. 1975, Eq.
\[ \omega^2 = (ke)^2 + \omega_p^2 / \sqrt{1 + \alpha^2} \]  

(29)

5. DISCUSSION

In this Letter we consider escape of high brightness coherent FRB emission from magnetars' magnetospheres. We come to a different conclusion than [Beloborodov 2021]: FRB pulses typically escape. Radiative losses of particles moving in the field of an FRB could in principle be important, but for a very restricted set of conditions. First, it requires a fairly slow neutron star with period \( P \geq 1 \) sec. Second, even for neutron stars with longer periods the single particle emission is suppressed by the non-dissipative ponderomotive acceleration of the background plasma by the incoming FRB pulse. Third, nonlinear Thomson scattering in a strong EM wave is suppressed by the LPM effects (long radiation formation length and the corresponding destructive interference): FRB pulse propagates not through a collection of single scatterers but through a continuous medium: wave propagate non-dissipatively, with only a slightly modified dispersion.

In some case radiation effects of FRB-accelerated particles on external perturbation may be important and may lead to observable weak UV/soft X-ray pulse that could in principle be detected by the sensitive instruments like Chandra.

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6. DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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