

Are fast radio bursts produced by large glitches of anomalous x-ray pulsars?

Abstract

Phase transitions within anomalous X-ray pulsars (AXPs) and soft γ -ray repeaters (SGRs) can lead to mini contractions. Such contractions produce pulsar glitches and shock break outs from their surface accompanied by thermal X/ γ -ray emission. Highly relativistic dipolar e^+e^- bunches launched from the pulsar polar caps emit fast radio bursts (FRBs) of narrowly beamed coherent curvature radiation, visible from cosmic distances if they point in the direction of Earth. Although the associated bursts of surface X/ γ -rays are nearly isotropic, and many orders of magnitude more energetic than the FRBs, they are detectable by the current all sky X-ray and γ -ray monitors only from our galaxy and nearby galaxies.

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Introduction

Fast radio bursts (FRBs) are short radio pulses of length ranging from a fraction of a millisecond (ms) to a few ms from extragalactic sources.¹ They were first discovered in 2007.² Their extragalactic origin was indicated by their dispersion measures and by their isotropic distribution in the sky.¹ Their estimated distances from their dispersion measure and radio fluence implied an energy release by an isotropic FRB in GHz radio waves roughly between 10^{37} erg and 10^{42} erg.¹

By the beginning of 2016, the lack of repeating pulses among FRBs known at that time, despite hundreds of hours of follow-up time,^{2,3} led to the wide spread belief that FRBs are one-time events. However, FRB121102,⁴ was followed by many more FRBs from the same source. Additional constraints on the nature of FRB 121102 were provided in 2017 by the precise localization of its source using the Karl Jansky Very Large Array.⁵ Radio observations using the European Very Long Baseline Interferometry Network and Arecibo provided compelling evidence for its positional association with a low-metallicity star-forming dwarf galaxy at a redshift $z=0.192$.⁵ This redshift, corresponding to a luminosity distance of \approx Gpc, was consistent with that obtained before from its dispersion measure, which supported the estimated isotropic equivalent energy release of cosmological FRBs being between 10^{37} erg and 10^{42} erg¹ in the radio band.

Moreover, FRB 180814⁶ and 8 additional FRB sources discovered last year by the Canadian Hydrogen Intensity Mapping Experiment (CHIME)⁷ were found to be repeaters, and 16.3 days periodicity was found in the repeating activity of FRB 180916 observed with the CHIME telescope.⁸ They ruled out the possibility that cataclysmic events, such as stellar explosions or stellar mergers, are a common source of all types of FRBs.⁹ However, they have not ruled out the possibility that single event FRBs and repeaters do have a common origin.

The sub-ms rise time of FRB pulses plus causality implies that FRBs are produced by very compact sources such as pulsars. Further indication of a pulsar origin of extragalactic FRBs is an average pulse shape (after correcting for dispersion) similar to that of radio pulsars.² But, perhaps the strongest evidence so far for a possible FRB-pulsar association came on April 28, 2020. A double peak FRB 200428 was detected¹⁰ from the direction of the Galactic soft gamma

ray repeater 1935+2154, which coincided in time (after correcting for dispersion) with a double spike X-ray flare from that source.¹¹ Although FRB 200428 was a thousand times less bright than typical extragalactic FRBs,¹⁰ it raised the possibility that both Galactic and extragalactic FRBs are produced by soft gamma ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs).¹⁰ Probably, only extragalactic FRBs that point very near the direction of Earth, are detectable from large cosmological distances, while Galactic FRBs, because of their proximity, are detectable up to much larger viewing angles. As in the case of gamma ray bursts (GRBs), the strong dependence of the equivalent isotropic energy and luminosity of FRBs on their viewing angle yields, on average, much larger isotropic equivalent energy, peak energy, and peak luminosity, of extragalactic FRBs compared to those of Galactic and very nearby FRBs.¹²

Moreover, large pulsar glitches have been seen to coincide within errors with giant x/soft gamma-ray flares of Galactic SGRs/AXPs.¹³ Such glitches may have been produced by mini contractions of pulsars following starquakes or internal phase transitions.¹⁴ They raise the possibility that such mini contractions lead to shocks break out from the surface of pulsars. Such shocks break-out in SGRs/AXPs, although much weaker, are analogous to those observed in core collapse (CC) supernova explosions (SNe) of massive stars.¹⁵ However, in SGRs/AXPs, such shocks break-out are expected to occur very shortly after the mini contraction. This is because of the much smaller size and much shorter dynamical time scales within pulsars due to their enormous density compared to those of massive stars. Shocks from starquakes in the crust layer of pulsars can reach the surface directly and produce a hot area on the surface of the pulsars. Mini contraction following internal phase transition can produce much stronger shocks which can be reflected from the center of the pulsar and break out from its entire surface.

By now, improved estimates of the distance to several SGRs, allow critical tests of whether the x/ γ -ray emission from large flares of SGRs are consistent with being thermal radiation from the surface of neutron stars. Indeed, as will be shown below, the record giant flare observed so far from an SGR, i.e., that of SGR 1806-20 on 27 December 2004,¹⁶ and the intermediate x/soft γ -ray flare observed on 12 April 2005 from SGR 1935+2154¹⁷ are consistent with being thermal emissions from the entire surface of a canonical neutron star. In all other cases where such tests were possible, the emitting surface area was equal or smaller than that of a canonical neutron star.

All together, the above seems to suggest that FRBs are produced by large glitches of SGRs/AXPs in external galaxies. But, as we shall show below, only a small fraction of the total gravitational energy release in SGR glitches produced by mini contractions, is used to spin up these pulsars. Most of the released energy is emitted as a burst of isotropic thermal x/soft γ -rays, but it is detectable by the current all sky x/ γ -ray monitors only from SGRs within our galaxy and nearby galaxies. Part of the released energy in glitches is emitted as a coherent curvature radiation from highly relativistic dipolar e^+e^- plasmoids launched from the magnetic poles along the direction of the pulsar magnetic moment.¹⁸ Such curvature radiation in the radio band is beamed mainly along the initial direction of motion of the dipolar jets. Those which happen to be beamed in/near the direction of Earth, are detectable by the largest radio telescopes/arrays up to very large cosmological distances as an FRB with characteristic pulse shape, peak energy and a very large linear and a much smaller circular polarization.¹⁹

FRBs from pulsar glitches

A pulsar glitch²⁰ is a sudden increase in the pulsar's rotational frequency, which usually decreases steadily due to braking provided by the emission of radiation, winds and high-energy particles. The exact cause of such glitches is still unknown. The prevailing view is that they are caused by an internal process within the pulsars such as an increase in the pulsar's crust rotational frequency by a brief coupling of an hypothesized pulsar's faster-spinning superfluid core²¹ to the crust, which are usually decoupled. This brief coupling transfers angular momentum from the core to the crust of the pulsar which causes an increase in its observed rotational frequency.²²

An alternative hypothesis for the origin of pulsar glitches is near surface starquakes/internal phase transitions which involve a sudden gravitational contraction of the pulsar that decreases its moment of inertia and speeds up its rotation within a very short time. The relatively small size of neutron stars and their very high density ρ yield a dynamical time scale $\sim 1/\sqrt{G\rho} \sim 0.1$ ms, for mini contractions, which can explain the observed short pulse duration of FRBs. A large angular momentum may suppress contraction in fast rotating pulsars. It may explain why large glitches are much more prevailing in the slowly rotating SGRs/AXPs than in ordinary pulsars, and are extremely rare in ms pulsars.²³

Shock break out flares in SGRs/AXPs? A sudden mini contraction of a slowly rotating pulsar, following a starquake or an internal phase transition, may produce a shock wave, which converges towards the center and reflected back towards the surface. Like in core collapse supernovae explosions, the shock break out from the surface of the SGR/AXP is expected to produce a flash of radiation.¹⁵ The finger prints of such a shock break out flash from the surface of a pulsar are a black body spectrum and a surface area consistent with that of a neutron star. Although the spectral energy density was reported for several giant flares of SGRs, only in two of these cases the distance to the SGRs/AXP by now are known well enough to allow a critical test of whether the lightcurve of the flare shows evidence for a shock break out from a pulsar. They include the giant flare of SGR 1806-20 on 27 December 2004¹⁶ and the large burst of SGR 1935+2154 on 12 April 2005.¹⁷

The giant flare of SGR 1806-20 on 27/12/2004 had an initial spike of a width $W \approx 0.125$ s, a total energy $E(\text{spike}) \approx (1.2 \pm 0.3) \times 10^{46}$ erg¹⁶ assuming isotropic emission at a distance $D = 8.7 + 1.8 / - 1.5$ kpc,²⁴ and a black body like spectrum with a peak temperature $T \approx 265 \pm 15$ keV.¹⁶ Thus, the radius of the emitted source was

$$R \approx \left[\frac{E(\text{spike}) 4\pi\sigma T^4 W}{4\pi} \right]^{1/2} \approx 2.3 \pm 2.3 \text{ km}, \quad (1)$$

consistent with that of a canonical neutron star.

The intermediate flare of SGR 1935+2154 on 12/4/2005 had a double peak structure.¹⁷ The first peak had a black body spectrum with a temperature $T = 6.4 \pm 0.4$ keV. The assumption of isotropic emission at a distance 10 kpc has yielded¹⁷ $R \approx \sqrt{455+73 / -55} \approx 21 \pm 2$ km. However, recently the distance to SGR 1935+2154 has been estimated to be only²⁵ 6.6 ± 0.7 kpc, yielding $R \approx 4 \pm 3$ km, consistent with that of a canonical neutron star.

Energy release in pulsar glitches: Consider an SGR/AXP with a canonical neutron star properties; a mass $M \approx 1.4 M_\odot$, a radius $R \approx 10$ km, a period P (rotational frequency $\nu = 1/P$), and a moment of inertia $I \approx (2/5)MR^2 \approx 1.12 \times 10^{45} \text{ g cm}^2$, whose radius contracts in a major glitch by ΔR . Angular momentum conservation,

$$\Delta L \approx 2\pi I \Delta \nu + 2\pi \Delta I \nu = 0, \quad (2)$$

yields

$$2\Delta R / R = -\Delta \nu / \nu \quad (3)$$

and a rotational energy increase,

$$\Delta E_{\text{rot}} = (\Delta \nu / \nu) E_{\text{rot}} \quad (4)$$

in such a glitch. The sudden contraction of the pulsar is accompanied by a gravitational energy release,

$$\Delta E_g \approx (3GM^2 / 5R) (\Delta R / R) \approx (E_g / 2) (\Delta \nu / \nu), \quad (5)$$

where G is the gravitational constant. In SGRs/AXPs with a typical period $P \gtrsim 1$ s, the gravitational energy release in a glitch is by far larger than the increase in their rotational energy,

$$\Delta E_g \Delta E_{\text{rot}} \approx 3GM P^2 4\pi^2 R^3 \approx 1.4 \times 10^7 (P/s)^2. \quad (6)$$

According to the virial theorem, half the gravitational energy release is converted to internal kinetic energy, part of which is used to increase the pulsar rotational energy. However, since the gravitational energy in SGRs is much larger than the rotational energy, eq.(6) implies that ΔE_{rad} , the radiated energy from major glitches in SGRs/AXPs, is bounded roughly by

$$\Delta E_{\text{rad}} \leq (3/20) (GM^2 / R) \Delta \nu / \nu. \quad (7)$$

The largest glitches observed so far in SGRs/AXPs had $\Delta \nu / \nu \leq 10^{-5}$. For such glitches, eq.(7) yields $\Delta E_{\text{rad}} \approx 8 \times 10^{47}$ erg. Probably, the bulk of this energy, escapes as a short burst of neutrinos, like in core collapse SNe, followed by a short flash of surface thermal x/ γ -rays. However, because of the very small radius and the huge mean density of pulsars relative to those of massive stars, the short spike of thermal x/ γ -ray surface radiation from a shock break out following a pulsar glitch, can even precede the neutrino burst.

FRB- coherent curvature radiation?

The main observed properties of FRBs are those expected of narrowly beamed coherent curvature radiation²⁶ emitted by SGRs/AXPs following large glitches.

Spectrum: A characteristic frequency of the curvature radiation emitted by a bunch of highly relativistic electrons moving with a bulk motion Lorentz factor $\Gamma \gg 1$ along a track with a curvature radius ρ_c was defined as,²⁶

$$\nu_c = 3c\Gamma^3 / 4\pi\rho_c. \quad (8)$$

The spectral distribution of the radiated energy, $dW/d\nu$, has the standard synchrotron radiation spectral distribution²⁶ which, in vacuum, is a function of the ratio $x = \nu / \nu_c$. In the pulsar rest frame, to a good approximation $dW/d\nu \propto x^{1/3}$ well below its peak value at $x = 0.29$, and changes to $dW/d\nu \propto \sqrt{x} e^{-x}$ well above it.

Beaming: The curvature radiation from highly relativistic electrons moving along a curved magnetic field line is collimated into a narrow cone of opening angle $\approx 1/\Gamma$ along their direction of motion. Eq.(8) and the locally observed FRB peak frequencies around 1.5 MHz, which satisfy $\nu_p \approx 0.29\nu_c / (1+z) \sim 1.5(1+z)$ GHz, $\langle \Gamma \rangle \approx 90(1+z)^{1/3}$.

Pulse shape of FRB: If FRBs and ordinary pulsar pulses are produced by curvature radiation, then, *after correcting for dispersion and redshift*, FRBs are expected to have a pulse shape similar to the average pulse shape of Galactic radio pulsars. The fast expansion of the plasmoids and the decline of the energy density of the magnetic field with increasing distance from the pulsar yield a FRED (fast rise, exponential decay) energy fluence with a shape similar to that of GRBs pulses¹²

$$F(t) \propto [t^2 / (t^2 + \Delta^2)]^{2\alpha} e^{-\beta t} \quad (9)$$

where α , β and Δ , are constants, which vary between different FRBs, and t is the time since the beginning of the pulse.

Polarization: The curvature radiation is strongly polarized in the plane of curvature. As the radio beam sweeps across the line of sight, the plane of polarization rotates up to 180 degrees.²⁶

Periodic FRB activity? Pulsars in highly eccentric orbits around a massive star in compact binaries may suffer periodic glitches triggered by mass accretion episodes which take place mainly near perihelion. Such activity can yield semi-periodic FRB activity with a period equal to the orbital period of the MSP around the massive star.

$$T = \left[4\pi^2 \sqrt{G(M_{n*} + M_*)} \right]^{1/2} [R_p (1 - \delta)]^{3/2} \quad (10)$$

where M_{n*} and M_* are, respectively, the masses of the pulsar and the massive star in the compact binary, and δ and R_p are, respectively, the eccentricity and the perihelion distance of the MSP orbit around the massive star. In the case of the periodic FRB 180916, the observed period of its FRB activity was $T = 16.3$ days.⁸

The redshift distribution of FRBs: The birth rate of SGRs/AXPs is a constant fraction of the birth rate of neutron stars in core collapse supernova explosions of short lived massive stars, which traces the star formation rate. The very small characteristic age $\tau = P / 2\dot{P}$ of SGRs/AXPs compared to that of ordinary pulsars and the similar beaming of FRBs and long duration gamma ray bursts (LGRBs) imply that their production rates as a function of redshift are roughly proportional.

Threat to life: FRBs do not threaten life on nearby life supporting planets. But large glitches of AXP/SGRs which produce giant x/γ-ray flares do, independent of whether or not they were accompanied by an FRB. Although the electromagnetic and kinetic energy release in giant flares of AXP/SGRs is much smaller than that released in SN explosions, the much higher rate of their giant flares compared to the birth rate of AXP/SGRs, their very short duration, and their much harder radiation, produce a more serious threat to life on nearby life supporting planets. as was noticed in.²⁷

Discussion and Conclusion

The possibility that giant x/γ-ray flares of AXP/SGRs, which are widely believed to be slowly rotating magnetars -highly magnetized, slowly rotating pulsars with a surface magnetic field in excess of 10^{14} Gauss²⁸- are the main source of extragalactic FRBs has been raised recently following the discovery of FRB coincident with an X-ray flare from the Galactic SGR 1935+2154.¹¹ The power supply for both a steady X-ray emission and X-ray flares, which exceeds by far the observed rotational energy loss of AXP/SGRs, was claimed to be provided by the decay of their magnetic field energy.²⁸ If the rotational

energy loss of such pulsars is entirely by magnetic dipole radiation, then their magnetic field at the equator satisfies $B \geq 3 \times 10^{19} \sqrt{P\dot{P}} / s$,²⁹ which is widely adopted in estimating their dipole magnetic field.²⁸ Indeed, a magnetic field energy of the order of $B^2 R^3 / 10$,²⁹ can power both their steady isotropic X-ray emission and their giant flares, while their FRBs could be produced by short emission of highly beamed coherent curvature radiation. But, despite the wide belief that AXP are magnetars that spin down by magnetic dipole radiation, and the decay of their magnetic field energy powers their x/γ-ray radiation and flares,²⁸ there is no solid evidence in support of these assumptions (see the Appendix).

In this paper we have suggested a mechanism by which SGRs/AXPs can produce narrowly beamed FRBs. We proposed that:

- AXPs are powered mainly by gravitational energy release in a slow contraction, rather than by the decay of an hypothetical ultra strong magnetic field,²⁸
- their spin down is dominated by emission of high energy charged cosmic ray and wind particles escaping along open magnetic field lines, rather than by magnetic dipole radiation,
- the gravitational energy release by a steady slow contraction powers their steady X-ray emission,
- a sudden short increase in this rate following a crustal starquake or an internal phase transition produces a glitch and shock waves whose surface break-out powers a short thermal X/γ-ray flare and emission of bunches of e^+e^- from their polar caps,
- such bunches produce FRBs - narrowly beamed short bursts of coherent curvature radiation in the MHz radio band, which are detectable only when they point in the direction of Earth,
- the beaming of FRBs can explain why no FRB has been detected before from the giant, presumably isotropic, x/γ-ray flare of SGR 1806-20 on 27 December 2004,³⁰⁻³² nor from other large x/γ-ray flares of Galactic and nearby extragalactic AXP/SGRs.

So far no x/γ-ray flares and/or FRBs associated with glitches of Galactic pulsars other than SGRs/AXPs were reported. Strong centrifugal barriers in ordinary pulsars and MSPs, compared to those in the slowly rotating AXP/SGRs, may suppress pulsar glitches with relatively large enough $\Delta\nu/\nu$ values that can produce observable extragalactic FRBs. Note that the only two MSP glitches³³ that were observed so far had $\Delta\nu/\nu \sim 10^{-10}$, which implied gravitational energy release of $\Delta E_g \approx 1.6 \times 10^{43}$ erg (see Eq.(7)). Such a gravitational energy release at a typical cosmological distance ~ 1 Gpc may generate an isotropic energy fluence below 10^{-10} erg/cm² at Earth. Such a fluence, however, is below the detection thresholds of current X-ray and gamma-ray full sky monitors, such as Swift, Konus-Wind, and Fermi GBM, which are above 10^{-8} erg/cm². Hence, they cannot exclude the possibility that glitches in extragalactic MSPs produce narrowly beamed FRBs, in association with an isotropic X/gamma-ray burst below their current detection thresholds.

Note, also, that the current observational information on glitches in MSPs is limited to old MSPs. Currently, nothing is known on glitches in very young MSPs, which prevents a definite conclusion on whether, they are also a source of extragalactic FRBs.

Appendix: A Magnetar Identity of AXP/SGRs - Myth Or Reality ? By definition, magnetars are neutron stars whose dipole magnetic field exceeds 10^{14} Gauss.²⁸ Anomalous X-ray pulsars (AXPs) and soft gamma ray repeaters (SGRs), are slowly rotating pulsars whose rotational energy loss is too small to power their observed X-ray

luminosity. They are widely believed to be powered by the decay of their estimated huge magnetic field energy. However, their estimated magnetic field is based on the assumption that they spin down by magnetic dipole radiation. Such an assumption yields a polar magnetic field,

$$B^2 \sin^2 \alpha = 3c^3 I P \dot{P} 2\pi^2 R^6. \quad (11)$$

For a canonical neutron star of a mass $M \approx M_{Ch}$, where M_{Ch} is the Chandrasekhar mass limit of white dwarfs, $I \approx (2/5)M_{Ch} R^2 \approx 1.12 \times 10^{45} \text{ g cm}^2$, Eq.(11) yields a polar magnetic field

$$B_p \sin \alpha \approx 6.4 \times 10^{19} [P \dot{P} / s]^{1/2} \text{ Gauss} \quad (12)$$

where α is the angle between the magnetic dipole moment and the rotation axis. Eq.(12) yields B_p value in excess of 10^{14} Gauss for most of the known AXPs/SGRs.²⁸

Eq.(12), which has been used to establish the magnetar identity of SGRs/AXPs,²⁸ is valid only if magnetic dipole radiation (MDR) dominates their spin down. However, if the spin down rate of a pulsar by other emissions, such as cosmic rays, particle winds, and gravitational waves is much larger than that by MDR, then eq.(12) overestimates by far the true value of their B_p . In fact, the loss of angular momentum of AXPs/SGRs can be dominated by emission of highly relativistic charged cosmic ray particles. Such cosmic rays gyrate along the magnetic field lines and escape when they reach the pulsar's light cylinder of a radius $r = c / \omega$ around the pulsar's rotation axis. If the high energy cosmic ray (CR) luminosity of a pulsar is $Lum(CR)$, then the loss rate of angular momentum by highly relativistic charged cosmic ray particles satisfies

$$\dot{L}_{CR} = \dot{n}_i |r \times p_i| \approx Lum(CR) / \omega, \quad (13)$$

where \dot{n}_i is the escape rate of CR particles from the light cylinder and $p_i \approx E_i / c$ is their momentum. Such a cosmic ray luminosity can dominate the spin down of SGRs/AXPs and invalidate their estimated magnetic field from the assumption that MDR dominates their spin down. Moreover, the "anomalous" X-ray emission of AXPs can be a surface emission powered by gravitational energy release in a slow contraction ($R / \dot{R} \gtrsim 10^5$ year).

Moreover, the assumption that a sudden decay (within a few ms) of the estimated ultra strong magnetic field of SGRs/AXPs powers their giant flares was contradicted by the fact that the product $P\dot{P}$ has not changed significantly³⁰ during the giant flare of SGR 1806-20 on 27 December 2004!¹⁶

Furthermore, the interpretation of absorption features observed in the X-ray spectrum of AXPs/SGRs as due to transitions between Landau levels of protons, rather than electrons, in their near surface magnetic field,³¹ results in a magnetic field strength that is $(m_p / m_e) \approx 1830$ times stronger than that obtained for electron transitions, which have yielded $B \sim 10^{12}$ Gauss typical of ordinary young pulsars. However, the constant magnetic field approximation in the pulsar magnetosphere is unreliable. Moreover, the absorption cross section for proton transitions between Landau levels is suppressed by a factor $(m_e / m_p)^2$ compared to that of electrons like the suppression of synchrotron radiation and Compton scattering by protons relative to electrons, which makes the proton interpretation very unlikely.

Note also that in a couple of cases, the assumption that AXPs/SGRs spin down by MDR has yielded a surface magnetic field similar to that of ordinary pulsars, i.e., much smaller than that expected in magnetars. E.g., $B < 7.5 \times 10^{12}$ Gauss at the equator was obtained for SGR 0418+5729,^{32a} and $B \sim 2.7 \times 10^{13}$ Gauss for SGR 1822-

1606.^{32b} However the assumption that MSPs spin down by MDR has yielded a magnetic field strength $B \leq 10^{10}$ Gauss for all MSPs with a measured P / \dot{P} . But, unlike AXPs/SGRs, all these MSPs are rather old ($P / 2P \geq 10^7$ y), and thus do not exclude the possibility that very young MSPs can be magnetars, i.e., born with a magnetic field which exceeds 10^{14} Gauss.

All together, so far there is no single solid evidence that slowly rotating AXPs/SGRs are magnetars.

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