FRBs from Low-twist Magnetars


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Fast Radio Bursts

- Extragalactic pulses of observed 1-50 ms duration
- “coherent” with brightness $T \gg 10^{30}$ K
- Multiple repeaters - FRB 121102 and CHIME repeater(s)
- Isotropic equivalent energy of $>10^{37}$ erg
- Some exhibit high polarization (some linear, some circular, FRB 121102 is 100% linearly polarized)

Petroff, Hessels, and Lorimer (2019)
Figure 7. Pulses detected from the first 30 minutes. The asterisks * indicate that the pulses have already been reported in Gajjar et al. (2018). For all plots, time on the horizontal axes indicates seconds since the start of observation. The frequency on the vertical axes is in GHz. Numbering on the top-left corner of each panel corresponds to Table 2. In cases when multiple pulses are shown in a panel, the numbering is in order of arrival time extrapolated to infinite frequency.

Figure 8. Detected pulses (continued). Same as Figure 7. Note that pulse morphologies vary and degree of visibility in the plot is subject to the frequency and time resolution shown.

Zhang et al. 2018

FRB 121102 — 93 GBT bursts (4-8 GHz) on August 6, 2017

Zhang+ 2018
Arrival times are non-Poissonian

Arrival times of pulses are independent of the emission mechanism, and probe the trigger in the progenitor

Log character of arrival times suggestive of multiplicative trigger with “memory” of previous events or states → “sandpiles”, earthquakes and reconnection-like processes
For each iteration \((i)\), we measured the duration \((T_{90};i)\). The simulated durations \((T_{90};i)\) were normally distributed, and the mean of this distribution, \((T_{90};\mu)\), allowed us to calculate a correction factor \(\frac{FD}{C_{17}1/C_{01}}\). The corrected distribution is shown in Figure 4. The best-fit mean is 99.31 ms, with a range of 14.4–683.9 ms for one standard deviation.

3.1.6. Burst Waiting Times

SGR waiting times \((T_{1};C)\), defined as the temporal separations of adjacent bursts, are found to follow lognormal distributions (Goelho Y et al. 1999, 2000). We measured the waiting time for the 1E 2259+586 events, excluding those interrupted by Earth occultations. Figure 10 displays our distribution with the best-fit lognormal model as determined by maximum likelihood testing. The best-fit parameters are a mean of 46.7 s and a range of 10.5–208.4 s for one standard deviation, with reduced \(\chi^2 = 0.6\). We find no correlation between the burst energy or duration and either the waiting time until the next burst or the elapsed time since the previous burst. Note, however, that the burst rate clearly decreased during the observation (see Fig. 1). This is made clear by the bottom panel of Figure 10, which shows a correlation between the waiting time \((T_{1};C)\) and the burst peak time \((t_{p})\). We fit this correlation to a power-law model using least-squares fitting, which reveals that \(t_{p} = 0.11t_{0.8}\). This correlation implies that the mean of our waiting time distribution depends on the time at which we started observing the outburst. We find no correlation between the burst energy or duration and when the bursts occur.

3.2. Burst Spectroscopy

3.2.1. Individual Burst Spectra

Spectra for each burst were extracted with the 256 spectral bins over the PCA range grouped by a factor of 4, in order to increase the signal-to-noise ratio per spectral bin. The same background intervals selected in measuring \(T_{90}\) were used in the spectral analysis (see \(x\)). In all spectral analyses, energies below 2 keV and above 60 keV were ignored, leaving on average 33 spectral channels for fitting. The regrouped spectra, along with their background estimators, were used as input to the X-ray spectral fitting software package XSPEC. Response matrices were created using the FTOOLS xtefilt.
Power-law Fluence/Luminosity Distributions

FRB 121102 — 93 GBT bursts

\[ \mathcal{E}_{\text{iso}} \lesssim 3 \times 10^{39} \left( \frac{F}{600 \, \text{Jy} \, \mu\text{s}} \right) \left( \frac{\Delta W}{4 \, \text{GHz}} \right) \left( \frac{d_L}{1 \, \text{Gpc}} \right)^2 \text{erg}. \]

High energy cutoff of about \(10^{41}-10^{42} \text{ erg} \) (\(10^{44} \text{ erg/s}\)) in the luminosity function of FRBs

Not implausible radio efficiencies of the calorimetric short burst energy release are required for the FRB
What are magnetar short bursts?

- ~10 - 500 ms duration, typically 100 ms, with shorter rise time
- In any given burst, evidence of hot and cool BBs with vastly different emission areas but similar luminosity $R^2 \sim T^{-4}$
- $\rightarrow$ implies coupling in the closed field line zone of the magnetosphere, and confinement
- Hot BB with small area = magnetic footpoints and return currents
- Cool BB with large area = thermalized pair plasma in the flux tube
- Burst energetics are low enough such that magnetic dominance should be maintained in a magnetar, i.e. $\sigma \gg 1$
What are magnetar short bursts?

- QPOs (~0.1 kHz) associated with crustal-torsional oscillations strongly suggest short bursts occur at very low altitudes and are associated with the NS crust
- Such crustal oscillations damp on a timescale of ~1-2 s due to core-crust coupling (e.g. Levin 2006)

QUASI-PERIODIC OSCILLATIONS IN SHORT RECURRING BURSTS OF MAGNETARS
SGR 1806–20 AND SGR 1900+14 OBSERVED WITH RXTE

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QUASI-PERIODIC OSCILLATIONS IN SHORT RECURRING BURSTS
OF THE SOFT GAMMA REPEATER J1550–5418

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FRB 121102’s NS must not be a fast rotator

FRB 121102 — 100% linearly polarized with PA fixed during a burst and modestly varying between bursts

Contrast: PA swings during pulses of radio pulsars from polar cap emission

Everett and Weisberg (2001)

Michilli+ (2018)
Twisted Magnetospheres

- Known galactic magnetars must have modestly twisted magnetospheres to support persistent emission
- A current system is set up to support the twist:

\[ \dot{J}_{\text{twist}} = \frac{c}{4\pi} |\nabla \times B| \sim \frac{c}{4\pi} \frac{B}{R_*} \sin^2 \theta_0 \Delta \phi \]

\[ \rho_{\text{twist}} \sim \dot{J}_{\text{twist}} / c \]

\[ \rho_{\text{GJ}} \sim \frac{B}{cP} \quad \rho_{\text{twist}} \gg \rho_{\text{GJ}} \]

\[ \frac{e n_e}{4,670 L_{X,35} P} \approx \frac{|\rho_{\text{GJ}}|}{\varepsilon_{\text{rad}} \langle \gamma_e \rangle B_{15} R_6^2} \]

Baring & Harding (2007)
FRBs from crustal dislocations

If crustal dislocations occur with wavelength $\lambda \sim 10^4$ cm at a frequency $\nu \sim 0.1$-1 kHz, and if the charge density is sufficiently high, the energy is dissipated by a plasma wave interactions and fluid-like processes ($E$ immediately screened)

$$E \sim \frac{\nu}{c} B \sim \frac{2\pi \nu \xi}{c} B$$

$$\rho_{\text{burst}} \sim \frac{1}{4\pi} \frac{E}{\lambda} \sim \frac{1}{2} \frac{\xi \nu}{\lambda c} B$$

If the charge density is low, however, intense particle acceleration and pair cascades must occur to satisfy the current demanded by the field dislocation(s)

$$\rho_{\text{burst}} > \max\{\rho_{\text{twist}}, \rho_{\text{GJ}}\}$$

(yielding) strain: $\sigma \equiv \frac{\Delta x}{x} \sim \frac{\xi}{\lambda} \sim 10^{-3} - 10^{-2}$

$\nu$ set by the characteristic kHz scale of observed QPOs

This is a necessary (but not sufficient) condition for FRBs in this model

From the condensed matter physics of NS crusts
Conditions for FRBs from magnetar short bursts

\[ \rho_{\text{burst}} > \max\{\rho_{\text{twist}}, \rho_{\text{GJ}}\} \]

- Most (>50%) FRBs ought to yield short bursts, but not all short bursts should result in FRBs
- \( \rightarrow \) slow rotator with low magnetospheric twist
- Duration of FRB pulses set by characteristic plasma-filling time of flux tubes

\[ \Delta \phi \lesssim \frac{2\pi R_\star}{c} \nu \frac{1}{\sin^2 \theta_0} \frac{\xi}{\lambda} \approx 0.003 \nu_{\text{kHz}} \sigma_{-3} \]

Low-twist condition (independent of B!)

\[ P \gtrsim \frac{2}{\nu_{\text{kHz}} \sigma_{-3}} \quad \text{sec} \]

Slow rotator condition (\( \Delta \phi = 0 \))

\[ \xi \gtrsim \frac{2\lambda}{\nu P} \approx 2 \frac{\lambda_4}{\nu_{\text{kHz}} P_{10 \text{ s}}} \quad \text{cm} \]

Threshold amplitude \( \rightarrow \) implies lower bound to FRB energy/luminosity function for a given \( P \)
Conditions for FRBs from short bursts

Resonant Compton drag must not interfere - photon densities cannot be too high

\[ \dot{\gamma}_{e, \text{burst}} \sim \frac{e}{(m_e c) E} \sim 10^{15.5} B_{14} \nu_{\text{kHz}} \sigma^{-3} \lambda_4 \quad \text{s}^{-1} \]

\[ \gamma_{\text{max}} \sim \frac{e \Delta \Phi_{\text{max}}}{m_e c^2} \sim 10^9 \nu_{\text{kHz}} \sigma^{-3} \lambda_4^2 B_{14} \]

\[ \gamma_{e, \text{RRLA}}^{\text{CR}} \approx 9 \times 10^7 \left( B_{14} \nu_{\text{kHz}} \xi_1 \rho_{c,7}^2 \right)^{1/4} \]

For typical parameters for crustal magnetic dislocations, efficient magnetic pair production requires surface \( B > 10^{12} \) - \( 10^{13} \) G for above-threshold pair production in CR RRLA

\[ B \gtrsim 3 \times 10^{13} \left( \frac{\chi_0 \rho_{c,7}^{1/2}}{\xi_1^{3/4} h_1 \nu_{\text{kHz}}^{3/4}} \right)^{4/7} \text{ G} \]
Minimum recurrence time

- Core-crust damping (e.g. Levin 2006) limits recurrences to within $\sim 1$-$2$ s
- Interestingly, the longest cluster of repetitions in Zhang+ (2018) persists for 2 seconds
- Within this $\sim 1$-$2$ s, the charges must clear a flux tube prior — the timescale of this is pair multiplicity times burst duration for the critical/twist burst amplitude $\rho_{\text{twist}} \sim \rho_{\text{burst}}$
- If burst amplitudes $\xi$ are large enough, then recurrences may occur on crustal oscillation periods of 1-10 ms

**FRB recurrence time** $\gtrsim 1/\nu_{\text{osc}}$ or $\kappa\tau_{\text{ms}}$

![Histogram and distribution plots](image)
Propagation Effects

- Vacuum birefringence is unimportant for radio frequencies
- The characteristic scale for both emission and propagation effects is the local plasma frequency

\[ \nu_e \lesssim \frac{1}{\sqrt{2\pi}} \omega_B^{1/2} \sigma^{1/2} \nu_{osc}^{1/2} \sim 17 B_1^{1/2} \sigma^{-3} \nu_{osc, kHz}^{1/2} \quad \text{GHz} \]

- For 1 GHz emission, it must arise from about 7 R* or the plasma must be relativistic for transparency — both are plausible
- PA may be “frozen in” by “adiabatic walking” of the X-mode within about

\[ \frac{r_{fo}}{R_*} \lesssim 18 B_0^{1/3} R_B^{1/3} a_{-1/3}^{0,5} \nu_{em, GHz}^{-1/3} \sigma^{-3} \nu_{osc, kHz}^{1/3} \]
Summary and Outlook

- Repeating FRBs like FRB 121102 are proposed to originate from magnetars undergoing crustal slippages which are known produce high-energy “magnetar short bursts”

- Most (>50%) FRBs ought to yield short bursts, but not all short bursts result in FRBs

- Future: time-coincidence confirmation for nearby FRBs with short bursts — must be very close O(1 Mpc) with current instruments

- PA variation → conditions are sufficient that adiabatic walking can occur of radio propagation, so PA variation could be driven by geometry

- Prediction: if bursts during slow heterogeneous untwisting, small DM variation may have the imprint of the rotator’s period

- Prediction: find period in PA variation? Need a large (100s) sample of FRBs with PAs

- Prediction: QPOs in large samples burst repetition clusters?

- Prediction: Repetition clusters which persist beyond 1-2 s should be rare due to core-crust damping

- Prediction: Signals above a few MeV should not be seen in time-coincidence with FRBs (but a MWNe may be present)
Backup Slides
FRBs and “Magnetar Short Bursts”

- Lognormality is just a parabola in log-log (low-order approximation of a humped distribution at the peak)
- Lognormality of waiting times is observed in magnetar short bursts episodes → loguniform character in arrival time
The First Repeating FRB?

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DISCOVERY OF MILLISECOND RADIO BURSTS FROM M87

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ABSTRACT

Highly dispersed radio pulses have been detected from M87 at radio frequencies of 430, 606, and 1420 MHz. The pulse sweep rates scale with the third power of the observing frequency as expected from the cold plasma law. The sweep rates correspond to dispersion measures in the range 1–5 × 10³ parsec cm⁻³. The pulses frequently appear grouped together separated within the group by approximately 50 ms. Peak power levels of 100 Jy and temporal widths of a few ms for individual pulses are found, and the group repetition rate is of the order of 1 s⁻¹.

Subject headings: galaxies: individual — radio sources: galaxies

Exhibited features associated with modern repeating FRBs:

• Millisecond duration
• Multiple repetitions in clusters
• Luminosity of 10⁴⁰ erg/s
• Frequency drifts?

Unconfirmed in observations which followed, but these did not rule out episodic behavior
Dynamic spectra of the bursts (see Table 1), each dedispersed to DM = 560.5 pc cm$^{-3}$, and using a linear scaling in arbitrary units (the bursts are not flux calibrated). The plotted dynamic spectra have the following time/frequency resolutions: AO-00: 0.33 ms/25 MHz; AO-01-13 and GB-01-04: 0.041 ms/6.25 MHz; GB-BL: 0.041 ms/55.66 MHz. The narrow horizontal stripes are the result of flagging RFI-contaminated channels. At the top of each panel, the band-integrated burst profile is shown, with the colored bars indicating the time spans of the sub-bursts used in the fitting. Bursts AO-01 to AO-13 are the new bursts detected with Arecibo. For comparison, AO-00 is burst #17 from Scholz et al. (2016); the white lines show the best-fit DM = 559 pc cm$^{-3}$ dispersive correction displayed here. GB-01 to GB-04 are the four new GBT bursts detected at 2.0 GHz, and GB-BL is one of the 6.5-GHz GBT Breakthrough Listen bursts presented in Gajjar et al. (2018).