On The Sources of Fast Radio Bursts

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ABSTRACT

This paper argues that repeating and apparently non-repeating Fast Radio Bursts are distinct classes of events produced by distinct classes of sources. I review evidence for that division, and discuss the statistics of these classes. They differ in temporal/spectral space, spectral/duration space and rotation measure; the first two differences indicate different emission processes, and the last indicates different environments. I discuss two of the many models of each class of source: black hole accretion discs for repeating FRB and hypermagnetized neutron stars (some observed to produce SGR) for apparently non-repeating FRB. Appendices suggest low cutoff frequencies of coherent emission that are consistent with these models and with known pulsars, and discuss the necessary conditions for acceleration of energetic particles.

1. Introduction

When a category of phenomena consists of two or more distinct sub-categories, understanding requires separating those sub-categories. A model that explains one sub-category may be apparently contradicted by data from another sub-category. Recognizing the existence of two or more distinct sub-categories means that a model that explains one sub-category will not be rejected because it fails elsewhere. Historic examples [Maccarone 2021] include the distinction between novæ and supernovæ, between Gamma Ray Bursts (GRB) and Soft Gamma Repeaters (SGR) and between Populations I and II Cepheids. In each case, very distinct events were conflated until further data (SN 1885 in the Andromeda galaxy and its recognition as a distant external galaxy, repetitions and spectral data of SGR 0525—66, the differing compositions of Populations I and II stars) established the
Fast Radio Burst (FRB) sources are phenomenologically divided into repeating and apparently non-repeating classes. However, this distinction might not be meaningful: Every repeater has a first detected burst, after which it is an apparent non-repeater, until a second burst is observed. In §2 I argue that the distinction is meaningful: the two phenomenologically defined classes differ in several ways other than repetition rate, and observational constraints on the repetition rates of the few extensively-monitored apparent non-repeaters are several orders of magnitude less than the observed repetition rates of well-studied known repeaters. This difference will either disappear or rapidly (quadratically in time) grow as the CHIME/FRB database accumulates. This is consistent with the suggestion (James, C. W. 2023; Yamasaki et al. 2024) that the majority of apparently non-repeating FRB may be repeaters because the reported low duty cycles only apply to the very few apparent non-repeaters that have been the subjects of extended observation.

If the distinction is only quantitative, qualitatively similar sources differ in repetition rate, and apparent non-repeaters eventually repeat. If it is qualitative, the two categories are fundamentally different and require different explanations. N. B.: “Apparently non-repeating” is defined phenomenologically, as the absence of repetitions in extant data; it need not imply never repeating, only that bursts are infrequent. For example, some repeaters have had burst rates of one per minute, while some apparent non-repeaters have been inactive over hundreds of hours, implying duty cycles differing by several orders of magnitude.

Ravi, V. (2019a); Hashimoto et al. (2020) argued that the rate of catastrophic events that destroy their source objects (supernovae, merging neutron stars, etc.) is insufficient to account for the observed rate of apparently non-repeating FRB, implying that they must repeat at some low rate or that only a few percent of apparent non-repeaters are
true one-offs from cataclysmic events. James et al. (2022); Zhang & Zhang (2022) have questioned the assumption that the volumetric occurrence rate of apparently non-repeating FRB was almost constant during the past.

§2 summarizes the arguments that repeating and apparently non-repeating FRB are qualitatively different, and that different sources must be sought for them. §3 proposes that repeating FRB are produced by accretion discs around black holes, likely of intermediate (between stellar and supermassive (Active Galactic Nucleus)) mass. §4 argues for the widely held hypothesis that apparently non-repeating FRB are produced by “magnetars”, hypermagnetized neutron stars whose emission is powered by their magnetostatic energy. The arguments presented here are phenomenological, rather than based on theoretical models of FRB emission, a much more difficult problem. Appendix A discusses a cutoff frequency on propagation of radiation in a magnetosphere while Appendix B discusses a necessary condition for the acceleration of energetic particles.

2. Two Distinct Classes

There are several ways in which repeaters differ from apparent non-repeaters.

2.1. Duty Cycle

A duty cycle $D$ may be defined, as a generalization of its definition in engineering in which it is the fraction of the time a system operates (for example, a radar transmitting a $1 \mu$s pulse 1000 times a second has a duty cycle of 0.001):

$$D \equiv \frac{\langle F \rangle^2}{\langle F^2 \rangle},$$

(1)
where $F$ is the flux. For a source that emits at a constant flux a fraction $D$ of the time this is equivalent to the engineering definition of $D$, but generalizes it to the astronomical case of a source whose intensity varies.

The first (Spitler et al. 2016) and likely best-studied repeating FRB 20121102A (the literature is extensive, but Cruces et al. (2021) is particularly thorough) has $D \sim 10^{-5}$, as may be estimated from the observation by the very sensitive FAST of $\sim 1$ ms pulses with typical intervals $\sim 100$ s (Li et al. 2021). In contrast, the best-observed apparently non-repeating FRB have $D \lesssim 10^{-8}$–$10^{-10}$ (Katz 2019). More recent studies (CHIME/FRB Collaboration 2023) are consistent with this. A telescope less sensitive than FAST would have observed a lower repetition rate than did Li et al. (2021), but still implying $D$ orders of magnitude greater than the upper limits on apparent non-repeaters.

The large number of sources (about 500 per year) observed by CHIME/FRB and its observing duty cycle $d \approx 0.02$ (30 minutes/day) imply either that in the fairly near future (1–10 years) the upper bound on the repetition rate of apparent non-repeaters will be reduced by orders of magnitude to

$$R \lesssim \frac{2}{N T d} \approx 0.2 \left(\frac{T}{y}\right)^{-2} y^{-1},$$

where $T$ is the duration of observation and $N \approx 500(T/y)$ is the number of apparently non-repeating FRB observed, or that repetitions of previously apparently non-repeating FRB will be observed.

For the recent CHIME/FRB catalogue (CHIME/FRB Collaboration 2021), $T \approx 1$ $y$ and $R \lesssim 0.2/y$. With a nominal FRB width $\Delta t = 3$ ms, the implied bound on the duty cycles of apparently non-repeating FRB

$$D \sim R \Delta t \lesssim 2 \times 10^{-11},$$

several orders of magnitude less than the duty cycles of known repeating FRB. Even if
repetitions are observed, their implied duty cycles are often orders of magnitude less than those of known repeaters, although there is some overlap. This distinguishes the majority of repeating FRB from the majority of apparently non-repeating FRB and implies different sources and mechanisms.

2.2. Spectro-Temporal Differences

The spectral and temporal behavior of repeating and apparently non-repeating FRB differ qualitatively (Hessels et al. 2019; Pleunis et al. 2021b). For example, Fig. 1 (Pleunis et al. 2021b) shows the “sad trombone” observed for repeaters but not for apparent non-repeaters. Fig. 2 (Pleunis et al. 2021b) shows the distributions of spectral running vs. burst width for repeating and apparently non-repeating FRB. Although as a function of a single variable these overlap, in two-dimensional space they are separated. Fig. 3 (Pleunis et al. 2021b) shows the distributions of burst bandwidth vs. duration. Again, the distributions are well separated in this two-dimensional space. The fact that in the two dimensional spaces the distributions of apparent non-repeaters and known repeaters are separated with only limited overlap indicates they are different classes of objects; only a small fraction of the apparent non-repeaters in these data have the properties of known repeaters.

2.3. Polarization

Repeating FRB have polarization that increases with increasing frequency. This is in contrast to pulsars, whose polarization typically is a decreasing function of frequency (Feng et al. 2022). Comparison to pulsars argues against models for repeaters in which their bursts are produced in the same region as pulsar radiation, within neutron star
Fig. 1.— De-dispersed dynamic spectra of bursts of four types, observed and discussed by Pleunis et al. (2021b). The first three sub-figures are apparent non-repeaters. The fourth is a repeater, and shows a drift to lower frequency, distinct from dispersion. This “sad trombone” effect is found for most repeating bursts, but is unusual for apparent non-repeaters (Bhandari et al. 2023).
Fig. 2.— Fitted spectral parameter “running” vs. burst length for several hundred bursts (numbers in figure) (Pleunis et al. [2021b]), with apparent non-repeaters (“one-offs”) green, repeaters purple and orange. The distributions of each variable, separately, overlap, but in the two-dimensional space there is a clear separation.
magnetospheres, although the interpretation of these observations might be confused by propagation effects (Biniamini, Kumar & Narayan 2022; Plavin et al. 2022). No such systematic trend in polarization has been reported for apparent non-repeating FRB, allowing for possible magnetospheric origin.

It does not argue against FRB models in which the energy source is a neutron star but emission occurs far away by mechanisms different from those that radiate pulsar pulses (Sridhar et al. 2021). In such models the energy source might be either rotational (a pulsar) or magnetostatic (a magnetar).

Some of the differences between repeaters and apparent non-repeaters are shown in Fig. 4.

3. Sources of Repeaters and The Magnetar Hypothesis

The most popular models of FRB (see Zhang (2023) for an extensive review) involve “magnetars”, neutron stars with extraordinary ($10^{14}–10^{15}$ Gauss) magnetic fields whose magnetostatic energy was proposed (Katz 1982; Thompson & Duncan 1992) to power Soft Gamma Repeaters (SGR). Their existence was demonstrated by the discovery of their quiescent counterparts, Anomalous X-Ray Pulsars (AXP), whose rapid spindown demonstrated the existence of the large magnetic fields required to power SGR outbursts.

3.1. Giant outburst of SGR 1806-20 did not make a FRB

A fortuitous out-of-beam radio observation (Tendulkar, Kaspi & Patel 2016) of the giant outburst of SGR 1806–20 did not observe a FRB. At its Galactic distance (about 300,000 times closer than a “cosmological” FRB at $z \sim 1$) and with 60 dB sidelobe
Fig. 3.— Burst bandwidth vs. durations (Pleunis et al. 2021b), with apparent non-repeaters (“one-offs”) green, repeaters purple and orange. The distributions in the two-dimensional space are nearly disjoint.

Fig. 4.— Repeaters have, on average, larger rotation measure (RM) than apparent non-repeaters (Feng et al. 2022).
suppression, a “cosmological” FRB would have been about 50 dB brighter than at \( z \sim 1 \). Yet no FRB was observed, implying either that FRB in general are beamed and observed if we are fortuitously in the beam or that SGR 1806–20 did not emit a FRB. Tendulkar, Kaspi & Patel (2016) set an upper bound on the fluence ratio \( \mathcal{F}_{\text{FRB}}/\mathcal{F}_\gamma \leq 10^7 \text{Jy-ms/(erg/cm}^2\text{)} \).

In contrast, the atypical Galactic FRB 20200428 was produced by the magnetar SGR 1935+2154. Its fluence ratio was \( \mathcal{F}_{\text{FRB}}/\mathcal{F}_\gamma \approx 2 \times 10^{12} \text{Jy-ms/(erg/cm}^2\text{)} \) (Bochenek et al. 2020a; Insight-HXMT 2020), more than five orders of magnitude greater than the upper bound on this ratio for SGR 1806–20. This established that these events are of different classes; either SGR 1935+2154 is not just a lower energy version of SGR 1806–20 or FRB 20200428 was not just a scaled down (but local) version of a “classical” FRB at cosmological distance.

### 3.2. Repeaters in compact dense plasma environments

The environment of FRB 20121102A has a multi-milligauss magnetic field (Michilli et al. 2018; Katz 2021a) and the dispersion measure (DM) of FRB 20190520B varies rapidly over a range of 40 pc-cm\(^{-3}\), implying an electron density \( n_e \sim 10^9 \text{cm}^{-3} \) (Katz 2022b). However, known magnetars are in supernova remnants, swept clear of dense plasma. SGR 1935+2154 is an example, and its associated FRB 20200428 shows no evidence of a dense magnetoionic plasma environment. Observations of pulsars in supernova remnants do not show the rapid variations of DM and RM observed in some repeating FRB.
3.3. Absence of rotational periodicity

Periodicity is expected if the energy source is a rotating magnetic neutron star. This applies whether the radiation is emitted in the magnetosphere or in a surrounding supernova remnant excited by a narrowly collimated beam. In order to produce a pulse of width $\Delta t$ at a distance $R$ from the source of the beam requires collimation within an angle $\Delta \theta \lesssim \sqrt{\Delta t/Rc}$ if the beam is directed to the observer, and $\Delta \theta \lesssim \Delta t/Rc$ if it is oblique (less likely, because then the radiation would not be collimated in the observer’s direction).

Rotating Radio Transients (RRAT) are pulsars most of whose pulses are nulled; RRAT are natural models for the temporal behavior of FRB, if FRB are produced by rotating neutron stars. The periodicity of RRAT is demonstrated by showing that their pulses are separated by integer multiples of an underlying period. No such period has ever been found for repeating FRB. The best data are those of Gajjar et al. (2018), who observed five bursts from FRB 20121102A within 93 s, giving four independent constraints on any such period. Confinement to such a short interval essentially eliminates the effects of any possible period derivative and of uncertainty in the times of the bursts. Attempts to find such a period have failed, in this object and in other repeating FRB.

A more systematic study of these data (Katz 2022a) calculated a figure of merit

$$FOM(P) = \sum_{i=C,D,E,F} \left( \frac{(t_i - t_B) - \text{NINT}[(t_i - t_B)/P]}{P} \right)^2,$$

where the bursts are denoted B, C, D, E and F, for the fit of the burst times to periods $P$, for $10^7$ periods from 0.432 ms to 1.2 h, evenly spaced in frequency from 231 $\mu$Hz to 2.31 kHz. The results are shown in Fig. 5.

The data of Li et al. (2021), 1652 bursts of FRB 20121102A, may be searched for periodicity using periodograms. These bursts were observed over several months, over which time even a very small frequency drift (neutron star spindown) would dephase a
Fig. 5.— Distribution of r.m.s. deviation from exact periodicity for hypothesized periods for five FRB 20121102A bursts in 93 s (Gajjar et al. 2018); Error bars are ±1σ. The smooth curve is expected for uncorrelated aperiodic bursts (shot noise). If the bursts were periodic that period would have had zero r.m.s. deviation; no such period is found.
periodogram by
\[ \Delta \phi = \frac{1}{8} \omega T^2, \]  
where \( T \) is the length of the data run. Hence it is necessary to analyze each separate data run, generally about one hour long, separately, reducing \( T \) from months to about a hour, and \( \Delta \phi \) by nearly seven orders of magnitude. An underlying periodicity would appear in each run, though possibly at slightly differing periods, even though it would be washed out in a periodogram of the entire dataset. These periods could be separated by less than their individual uncertainties.

The dataset of Li et al. (2021) includes 17 separate runs with at least 50 bursts each. These are analyzed and the distribution of periodogram amplitudes (summed over the 17 periodograms) shown in Fig. 6. The distribution is close to the Gaussian expected for “shot noise” burst times, somewhat broadened and skewed by the slow variations in activity of FRB 20121102A. A period in even one periodogram of the 17 would give an outlying amplitude and a persistent period would give a cluster of outliers, even though the individual periodicities would be dephased. The largest average normalized amplitude in the data is 1.706, consistent with shot noise.

Periodograms of 1–2 hour periods of intense activity, each comparable to a single observing session of FRB 20121102A (Li et al. 2021), of FRB 20180916B (Mckinven et al. 2023a) and a thorough study of more than 800 bursts from FRB 20201124A that considered possible source acceleration (as would be produced by a binary orbit) as well as fine substructure (Niu et al. 2022) also showed no evidence of periodicity.
Fig. 6.— Distribution of the the $3.6 \times 10^6$ averages of the normalized amplitudes of 17 single-session ($\geq 50$ bursts) periodograms of FRB 20121102A for periods from 1 ms to 1 hour, evenly spaced in frequency; data from Li et al. (2021).
3.4. Dense chaotic environments

The dispersion measures of FRB include contributions from our Galactic disc, the Galactic halo, the intergalactic medium, any galactic haloes along the line of sight (Simha et al. 2023), the host galaxy and the vicinity of the FRB source. The Galactic contributions can be estimated, but with substantial uncertainty. When the FRB source is identified with a galaxy of measured redshift the intergalactic contribution can be estimated with confidence. The host galaxy’s contribution is necessarily uncertain, but is plausibly of the same order as the Galactic contribution. At least one repeater (FRB 20190520B (Niu et al. 2021)) and at least one apparent non-repeater (FRB 20220610A (Ryder et al. 2023)) have large excess DM, but it is hard to distinguish between near-source and intergalactic origin.

The environments of some repeaters are extraordinary in other ways. The rest (source)-frame rotation measure (RM) of FRB 20190520B changed from about $-11000$ rad/m$^2$ to $+19000$ rad/m$^2$ over about 270 days, and then decreased to about $-37000$ rad/m$^2$ in the subsequent 150 days (Anna-Thomas et al. 2023), indicating a reordering of a compact magnetized environment. The repeater FRB 20121102A had even larger RM $\sim 100000$ rad/m$^2$, decreasing by about 30000 rad/m$^2$ over three years (Michilli et al. 2018; Wang et al. 2020; Hilmarsson et al. 2021), and indicating (when combined with changes in DM) magnetic fields in the range 3–17 milligauss (Katz 2021a). A study (Mckinven et al. 2023b) of 12 repeating FRB found variations in their (smaller) RM on time scales of months, again indicating chaotic magnetoionic environments unlike those observed around pulsars.

Even more remarkable are the observations of the DM of the repeating FRB 20190520B, that varied over a range of about 30 pc-cm$^{-3}$ on time scales of tens of s, as shown in Fig. 7 (data from Anna-Thomas et al. 2023). A straightforward interpretation (Katz 2022b) in terms of clouds of plasma moving in and out of the line of sight suggests electron densities
as high as \( n_e \sim 10^9 \text{/cm}^3 \). The requirement that a cloud with DM of 30 pc-cm\(^{-3}\) and this \( n_e \) be transparent at an observation frequency of 1.4 GHz implies that its temperature \( T \gtrsim 3 \times 10^6 \text{K} \). This is plausible for the near (DM/\( n_e \sim (10^{11} \text{cm}) \) environment of an accreting, perhaps intermediate mass, black hole.

Variations in DM and RM for repeaters obviously cannot be directly compared to the DM and RM of apparent non-repeaters, which are one-off observations. But the varying DM of FRB 20190520B and RM of the repeating FRB 20121102A are inconsistent with the evacuated interiors of the supernova remnants that surround soft gamma repeaters. The extraordinarily large RM of FRB 20121102A, even aside from its variation, is inconsistent with the observed RM of the apparent non-repeaters (Pandhi et al. 2024).

3.5. If Magnetars Don’t Make Repeating FRB, Then What Might?

1. Must not be periodic!

2. Must not be catastrophic!

3. Must be rare

4. Must be consistent with a dense chaotic magnetoionic environment

What satisfies these criteria?

Some black hole accretion discs (e.g. AGN, SS433 etc.) accelerate jets of energetic particles. Their lifetime is as long as there is a supply of matter to accrete, perhaps from a companion star, which may be the lifetime of that star. Accretion funnels are a natural collimating mechanism. However, they are not rare; there are many accreting black holes in our galaxy. Worse, Galactic binary black hole accretion discs are not observed to make coherent radiation, much less FRB.
Fig. 7.— $|\Delta \text{DM}|$ vs. $\Delta t$ for intervals between successive bursts of FRB 20190520B on MJD 59373; data from Table S3 of Anna-Thomas et al. (2023).
If the hypothesis (Katz 2017) that accretion discs around black holes make FRB is correct, the accretion discs that make FRB must differ in some manner from those of the much more numerous Galactic black hole X-ray binaries. One possible difference is as simple as orientation: their coherent radiation (including hypothetical FRB) may be very narrowly collimated along the disc axis. Appendix A discusses magnetospheric plasma cutoffs. If collimation is narrow enough, this would have attractive consequences:

- It might explain their rarity

- FRB luminosities would be several orders of magnitude less than their (forbidding) isotropic-equivalent luminosities

- Lifetimes could be as long as binary mass-transfer lifetimes (the decade of activity of FRB 20121102A without evident systematic change would not be a surprise)

- The environment of a mass transfer binary might explain the large and variable DM and RM observed in some repeating FRB

- FRB would then be identified as suitably oriented microquasars, whose orientation would be consistent with the absence of the double radio lobes of most microquasars.

Sridhar et al. (2021) suggested that FRB are distinguished from other black hole accretion discs by extraordinarily high mass transfer rates, resembling those of Ultra-Luminous X-ray sources (ULX), although at least some ULX are produced by neutron stars rather than black holes. This would contribute to the rarity of FRB without implying or requiring a similarity between the thermal emission of ULX and the coherent non-thermal emission of FRB.
3.6. Precession

Although individual outbursts of repeating FRB do not show the rapid periodicities characteristic of rotating neutron stars, the activity of two repeating FRB (FRB 20180916B (CHIME/FRB Collaboration 2020; Pleunis et al. 2021a) and FRB 20121102A (Rajwade et al. 2020) is modulated with long periods (16.35 d and 160 d, respectively). The times of the individual bursts are not periodic, but the bursts occur within periodic windows. There is significant phase scatter about exact periodicity, shown in Fig. 8, although the underlying period is apparently stable. The width of the active window depends somewhat on the frequency of observation (Pleunis et al. 2021a).

A number of explanations have been suggested for this periodicity. The phase jitter resembles that of the beams of SS 433 that jitter in angle. SS 433 is a mass transfer binary containing a 15\(M_\odot\) black hole that accelerates beams along the angular momentum axis of its precessing accretion disc. The close analogy between the temporal behavior of FRB 180916B and that of SS 433 supports the black hole accretion disc model of repeating FRB (Katz 2022c).

4. Apparently Non-repeating FRB

4.1. Constraints from repetition rate

The rate of apparently non-repeating FRB exceeds that of all known catastrophic events (Ravi, V. 2019a; Hashimoto et al. 2020). Most or all apparently non-repeating FRB must repeat, but so infrequently that no such repetitions have been observed.

There are constraints on the repetition rates of a few specific apparent non-repeaters:

- FRB 20190523 did not repeat in 78 hours (Ravi et al. 2019b), setting an upper limit
Fig. 8.— Phases of the 44 individual bursts of FRB 20180916B observed by Mckinven et al. (2023a) for the fitted period of 16.315 d (points), a bar graph of their distribution (solid) and the fitted Gaussian (dotted). If the phase jitter results from a random walk about exact periodicity, the observed Gaussian distribution is expected. The mean phase is defined as 0.5 and its standard deviation is 0.071.
on its repetition rate \( \lesssim 0.3/d \).

- FRB 20180924 did not repeat in 720 hours of less sensitive observations nor in 11 hours of more sensitive observations (Bannister et al. 2019); adjusting for sensitivity suggests repetition times \( \gtrsim 10^3\text{–}10^4 \text{ h} \).

- FRB 20210117A did not repeat in about 140 hours of subsequent observations, mostly by ASKAP with a detection fluence threshold about eight times lower than its originally detected fluence (Bhandari et al. 2023).

- A statistical study of 27 apparent non-repeaters over 383.2 hours found only one to repeat, and set statistical limits on any repetition behavior (James et al. 2020).

These constraints have been much tightened by CHIME/FRB (CHIME/FRB Collaboration 2023) and will continue to be tightened, or repetitions of apparent non-repeaters will be observed. CHIME/FRB stares at everything in the northern sky about 30 minutes per day (an observational duty cycle \( D \approx 0.02 \)), every day, and observes \( N \approx 500 \) sources per year. After a time \( T \), if no repetitions are observed the repetition rate would be constrained:

\[
R \lesssim \frac{1}{NDT} \sim \frac{0.1}{y} \left( \frac{T}{y} \right)^{-2}.
\]

Either a repetition will be observed or this bound will tighten rapidly.

### 4.2. Candidate Sources: Soft Gamma Repeaters ("Magnetars")

These have been popular candidates as FRB sources since their discovery for several reasons:

1. SGR are transients.
2. SGR giant outburst rise times are observed to be sub-ms.

3. SGR have plenty of energy (observed up to $10^{47}$ ergs).

4. Rare repetitions of giant SGR outbursts might explain the FRB event rate (giant outbursts guesstimated to occur $\sim 100$ times in a SGR lifetime).

5. Observed intervals $> 30$ y between giant SGR repetitions are consistent with apparent non-repetition of FRB.

### 4.3. FRB 20200428/SGR 1935$+2154$

This is the only confirmed (Bochenek et al. 2020a; CHIME/FRB Collaboration 2020) FRB/SGR association, although the “giant” (1.5 MJy-ms) FRB 20200428 at 6 kpc was too weak to have been detected at the distances $\gtrsim 10$ Mpc of all but one other FRB. Three much weaker repetitions of FRB 20200428 were detected (Kirsten et al. 2021), but at distances $\gtrsim 100$ kpc these would have been undetectable. At distances 100 kpc–10 Mpc FRB 20200428 would have been an apparent non-repeater. Subsequent spin glitches and an additional burst have been reported (Hu et al. 2024).

### 4.4. Problems with the Magnetar Model

1. No FRB was associated with the giant outburst of SGR 1806$-20$. A fortuitous simultaneous radio observation (Tendulkar, Kaspi & Patel 2016) set an upper bound about 50 dB lower than a “cosmological” FRB at the distance of SGR 1806$-20$ (110 dB from its closer distance minus 60 dB suppression of sensitivity at $35^\circ$ from the main beam).
2. FRB are coherent emission by bunched energetic charges, while SGR are thermal phenomena with the spectrum of an equilibrium pair gas.

3. The dense plasma inferred from the spectrum of SGR is opaque to all electromagnetic radiation.

4. SGR outburst durations are $\sim 100$ ms, much longer than the 0.1–10 ms durations of most FRB, (although Mereghetti et al. (2020) reported narrower substructure in a burst from SGR 1935+2154). However, this might be explained by the sub-ms rise times of giant SGR (Katz 2016).

4.5. Statistics of Apparently Non-Repeating FRB and SGR

The giant outbursts of SGR and apparent non-repeating FRB are both outliers from their distributions of lesser events (Katz 2021b). This is unusual in astronomy: Most distributions of astronomical parameters, including flux and fluence but also others, are well fit by (sometimes broken) power laws (e.g. FRB 20201124A (Kirsten et al. 2024)). Apparently non-repeating FRB and SGR are exceptions.

This can be parametrized by the ratios of the most extreme value of a parameter $x_1$ to the next-most extreme ($x_1/x_2$). Table 1 shows some examples; Confidence is the confidence with which the hypothesis that $x_1$ is consistent with the power law fitted to lesser events or objects can be rejected.

In each case in Table 1, with one exception, the most extreme object may be consistent with the power law fitted to the less extreme objects, indicating that they are qualitatively similar. The statistics of variable sources (AGN, 3CR) are likely biased to higher extreme values because the strongest sources are better observed, increasing the likelihood of catching unusual excursions to yet higher flux; this may explain their marginally significant
| Parameter                              | N     | $x_1/x_2$ | $\gamma$ | Confidence |
|----------------------------------------|-------|-----------|----------|------------|
| Stars (V-band)                         | 1.94  | 5/2       |          | 63%        |
| AGN (V-band)                           | 10    | 5/2       |          | 97%        |
| 3CR (extragalactic)                    | 298   | 8         | 5/2      | 96%        |
| 3CR (Galactic)                         | 38    | 8         | 2        | 87%        |
| 4U (Galactic)                          | 181   | 18        | 2        | 94%        |
| 4U (transients)                        | 12    | 3.5       | 2        | 72%        |
| SGR 1806−20 burst fluence              | 760   | $7 \times 10^4$ | 1.7     | 99.96%     |
| Crab Giant Pulses                      | > 1100| 1.25      | 2.8      | 33%        |

Table 1: Ratios of highest to second-highest fluxes and fluences $x_1/x_2$ from several astronomical catalogues. $N$, where applicable, is the number of objects in the catalogue, $\gamma$ is the fitted or theoretical differential slope, and Confidence is the confidence with which the hypothesis that $x_1/x_2$ is consistent with the power law can be rejected. References in [Katz](2022c).
disagreement with the extrapolated power laws. The one case in which the strongest event is clearly inconsistent with the power law is the giant outburst of SGR 1806−20. It must be qualitatively different from its lesser outbursts. This is usually attributed to a global reorganization of the magnetic field, in contrast to lesser localized flares.

Analogous analyses for various FRB statistics are shown in Table 2. The fluxes and fluences from various FRB catalogues (it is necessary to analyze each catalogue separately so that the sample be homogeneous) are all consistent with power laws, as are the outbursts of FRB 20121102A. The exceptions are the flux and fluence of the giant outburst of FRB 20200428, that are inconsistent, with very high statistical confidence, with extrapolations of the power laws estimated from its three lesser outbursts. FRB 20200428 is consistent with expectations for a lower energy analogue of the apparently non-repeating FRB at cosmological distances.

4.6. Why No FRB Associated with SGR 1806−20

The $10^{47}$ ergs/s SGR 1806−20 filled its magnetosphere with dense equilibrium pair plasma, preventing acceleration of energetic particles and escape of radio radiation. No particle acceleration or radio radiation is expected from any SGR with (isotropic) power $\gtrsim 10^{42}$ ergs/s. At energy densities corresponding to pair equilibrium at temperatures $k_B T > 22$ keV, space on scales of a neutron star’s inner magnetosphere is filled with dense pair plasma \cite{Katz1996}. The threshold temperature is a weak function of the length scale. The radiation from such a thermal plasma would be unbeamed, unlike FRB that are likely beamed, an alternative explanation.

This argument implies that apparently non-repeating FRB are produced by “intermediate” outbursts of SGR, with total power $\lesssim 10^{42}$ ergs/s. It is unclear how these
### Table 2: Ratios of most extreme to second most-extreme FRB. Some $\gamma$ are for a Euclidean universe, $\gamma$ for RM is for a SNR model, others are fits. Confidence is the confidence with which the hypothesis that $x_1/x_2$ is consistent with the power law can be rejected. Entries for FRB 20200428 refer to its four observed bursts, not comparison to other FRB. Details and references in [Katz](2022c).

| Parameter                  | N  | $x_1/x_2$ | $\gamma$ | Confidence |
|---------------------------|----|-----------|----------|------------|
| FRB Fluxes (Parkes)       | 31 | 4.3       | 5/2      | 89%        |
| FRB Fluxes (UTMOST)       | 15 | 1.37      | 5/2      | 38%        |
| FRB Fluxes (ASKAP)        | 42 | 1.15      | 5/2      | 19%        |
| FRB Fluxes (CHIME)        | 536| 1.33      | 2.4      | 33%        |
| FRB Fluences (Parkes)     | 31 | 1.1       | 5/2      | 17%        |
| FRB Fluences (UTMOST)     | 15 | 1.71      | 5/2      | 55%        |
| FRB Fluences (ASKAP)      | 42 | 2.1       | 5/2      | 67%        |
| FRB Fluences (CHIME)      | 536| 1.0       | 2.4      | 0%         |
| FRB 20200428 Fluxes       | 17000| 5/2 | > 99.9999% |
| FRB 20200428 Fluences     | 3600| 5/2      | > 99.999% |
| FRB RM                    | 19 | 200       | 5/4      | 73%        |
| FRB 20121102A Fluxes      | 93 | 1.55      | 1.7      | 26%        |
may differ from the Galactic SGR with much more energetic giant outbursts. For example, SGR that make FRB might have weaker magnetic fields than those that produce giant outbursts, or FRB may be produced by intermediate-scale outbursts of SGR that are capable of (and may also produce) giant outbursts. Galactic SGR should be monitored for FRB activity.

5. Distribution of FRB in the Universe

CHIME/FRB has provided a homogeneous catalogue (CHIME/FRB Collaboration 2021) of more than 500 FRB sources, most apparently non-repeating. This has enabled statistical studies that compare the distribution of FRB vs. redshift $z$ to the distribution of other objects and processes, specifically the star formation rate. Several studies (Zhang & Zhang 2022, Zhang et al. 2024, Chen et al. 2024) have found that the distributions differ, with FRB concentrated at small $z$ while the star formation rate was much larger in the more distant past (note, however, that Wang & van Leeuwen 2024 came to the opposite conclusion). Because the time lag from star formation to neutron star formation is cosmologically brief (the minimum initial stellar mass must be at least the Chandrasekhar mass $1.40M_\odot$ and is likely at least $6M_\odot$, stars with main sequence lifetimes of $\sim 3 \times 10^9$ y and $\sim 10^8$ y, respectively) this argues against young neutron stars as the sources of FRB. Whether resembling ordinary pulsars, whose duration of activity is $\sim 10^7$ y, or magnetars, whose duration of activity is $\sim 10^4$ y, the additional delay is insignificant. Old neutron stars may undergo catastrophic events, such as double neutron star mergers, after arbitrarily long delays, but these cannot explain repeating FRB and are insufficient in number to explain apparent non-repeaters (Hashimoto et al. 2020).

In contrast, the distribution on FRB in the universe is consistent with an origin in black hole accretion disc funnels because black holes live forever, gradually accreting mass.
Their number density only declines as a result of cosmic expansion, not nearly as fast as the star formation rate.

6. Conclusion

FRB and SGR are the two kinds of astronomical events whose most extreme members are true outliers, far exceeding extrapolations from lesser events. There are few or no other examples of such distributions (the Sun far exceeds other stars in apparent brightness, but this is a selection effect: the Earth must be habitable). This is evidence in support of the association of apparently non-repeating FRB (which FRB 20200428 would be if at a distance between about 100 kpc and 10 Mpc) with SGR. The fact that repeating FRB do not have flux or fluence outlier events confirms their qualitative difference from apparent non-repeaters.

Some suggestions for observations follow:

- Black hole accretion discs whose angular momentum axes might point to the Earth should be monitored for FRB or analogous activity, perhaps repeating. These should include both stellar-mass (X-ray binary) and supermassive (AGN) accreting black holes.

- Galactic (and extra-Galactic) SGR should be monitored for FRB activity, plausibly producing rare strong FRB and also FRB weaker by orders of magnitude but not more frequent by orders of magnitude. The STARE2 (Bochenek et al. 2020b) and GReX (Connor et al. 2021) systems are sensitive to such events.
A. Cutoff Frequency for Coherent Emission

A minimal hypothesis for coherent emission is that it has a cutoff frequency equal to the plasma frequency at the Goldreich-Julian charge density

$$\rho_{GJ} = \frac{\vec{B} \cdot \vec{\Omega}}{2\pi c},$$

where $B$ is the surface magnetic field and $\Omega$ the angular rotation rate of a pulsar. The hypothesis is that coherent structures cannot exist with fewer than $\mathcal{O}(1)$ electron per unit wavelength. If the electrons are moving relativistically then radiation from electrons separated perpendicular to the direction of motion by many wavelengths may radiate coherently, and the criterion is electrons per unit wavelength in the direction of motion and per wavelength times the Lorentz factor in the two transverse directions (X-ray laser undulators are an example).

The charge density of Eq. A1 corresponds to a plasma frequency, and hypothesized cutoff frequency (taking $\vec{B} \cdot \vec{\Omega} = B\Omega$),

$$\nu_p = \sqrt{\frac{B\Omega e}{2\pi^2 m_e c}}.$$  \hspace{1cm} (A2)

Numerically, for the Crab pulsar $\nu_p \approx 30$ GHz, for SGR 1935+2154 (FRB 20200428) $\nu_p \approx 10$ GHz. These cutoffs only apply near the stellar surface, where $B$ is maximum. For a dipole field $\nu_p$ falls off $\propto r^{-3/2}$. Nearly all millisecond pulsars have $B/P > 3 \times 10^{10}$ Gauss/s, where $P$ is the period, corresponding to $\nu_p > 400$ MHz; these objects are generally observed at low frequencies. Eq. A2 is consistent with these observations, and its predictions of cutoffs may be testable. The few pulsars that appear to violate this condition may be attributable to erroneously low $B$ inferred when low apparent spindown is the result of acceleration by the Galactic gravitational field cancelling a larger true spindown rate (Perera et al. 2019).

Eq. A2 is not applicable to the proposed accretion disc sources of frequently repeating
FRB because the disc is a source of comparatively high density plasma, without requiring pair production as in pulsars. Bursts may be emitted in the vacuum of an accretion funnel where the density may be much less than the Goldreich-Julian value. The observation of FRB 20180916B at frequencies as low as 110 MHz (Pleunis et al. 2021a) constrains the plasma density along the line of sight to the emission region to be \( n_e \ll 1.5 \times 10^8 \text{cm}^{-3} \). This is less than the density \( n_e \sim 10^9 \text{cm}^{-3} \) inferred from DM variations observed for FRB 20190520B (Anna-Thomas et al. 2023) in C-band (4–8 GHz), but at those higher frequencies the propagation condition is \( n_e \ll 10^{10} \text{cm}^{-3} \).

B. Conditions for Particle Acceleration

In order to accelerate energetic particles, necessary both for incoherent emission (as in AGN and radio sources) and for coherent emission (as in pulsars and FRB, if these particles drive a plasma instability), it is necessary that they gain energy from an electric field faster than they lose it to interaction with ambient plasma (by “Coulomb drag”) (Atzeri, Schiavi & Davies 2009). For a relativistic electron the ratio of these quantities defines an acceleration parameter

\[
A \approx \frac{Em_e c^2}{4\pi e^3 n \ln \Lambda},
\]

where \( E \) is the electric field, \( n \) the plasma particle density and \( \Lambda \) is \( 2m_e c^2 / I \) with \( I \) the ionization potential in a neutral medium or \( m_e c^2 / \hbar \omega_p \) in a plasma. \( \ln \Lambda \approx 20 \) in most astronomical environments, and is insensitive to their parameters. \( A > 1 \) is a necessary condition for particle acceleration.
B.1. Near-vacuum magnetospheres

In a rotating pulsar or magnetar magnetosphere the particle density may be very low, conducive to particle acceleration. The minimum density is the Goldreich-Julian density

\[ n = \frac{\vec{\Omega} \cdot \vec{B}}{2\pi ce}, \quad (B2) \]

where \( \vec{\Omega} \) is the rotation rate and \( \vec{B} \) the local magnetic field. Then, taking \( \vec{\Omega} \cdot \vec{B} = \Omega B \) and \( E = \Omega RB/c \) at a radius \( R \), the acceleration parameter Eq. \[B1\]

\[ A = \frac{Em_e^3}{2\ln \Lambda e^2} \approx \frac{m_e^2}{2\ln \Lambda(e^2/R)}. \quad (B3) \]

Because \( R \) is the overall system dimension, at least \( \sim 10 \) km, \( e^2/R \lesssim 10^{-24} \) erg and \( A \gtrsim 10^{17} \).

Such magnetospheres are natural sites for acceleration of energetic particles. The passage of accelerated electrons through background plasma, ambient or positrons created by pair production, may make excitation of plasma waves and coherent radiation, such as pulsar and FRB emission, almost unavoidable when there is no copious source (such as accretion) of thermal plasma to put the plasma in a magnetohydrodynamic regime.
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