The Sources of Apparently Non-Repeating FRB

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ABSTRACT
There are insufficient catastrophic events (collapse, explosion or merger of stars or compact objects) to explain the cosmologically local rate of apparently non-repeating FRB if each such catastrophic event produces a single FRB. Unless produced by some novel and unsuspected but comparatively frequent event, apparently non-repeating FRB must actually repeat many times in the lifetimes of their sources. Yet no such infrequent repetitions (in contrast to the frequent activity of FRB known to repeat) have been observed, constraining their repetition rates and active lifetimes. The absence of more frequent weaker but detectable repetitive outbursts in apparent non-repeaters resembles the distribution of SGR outbursts, with a large gap between giant outbursts and lesser outbursts. This suggests mini-SGR as sources, more energetic than SGR 1935+2154 associated with FRB 200428 but less energetic than SGR 1806–20 that had no associated FRB. Their largest radio outbursts would, at cosmological distances, be apparently non-repeating FRB and their X-ray and gamma-ray outbursts would be undetectable. The large gap between the strongest outburst of FRB 200428 and its lesser outbursts resembles the gamma-ray properties of individual well-observed SGR; at twenty times its actual distance, FRB 200428 would have been an apparent non-repeater.

Key words: radio continuum, transients: fast radio bursts

1 INTRODUCTION
I argue that repeating Fast Radio Bursts (FRB) and apparently non-repeating FRB are fundamentally different objects. Complementary to Katz (2022) about repeating FRB, this paper advances a hypothesis for the origin of apparent non-repeaters. It suggests, on the basis of statistical similarities of their distributions of strengths that they are more energetic relatives of FRB 200428/SGR 1935+2154 but unrelated to known repeating FRB.

The measured volumetric rate of apparently non-repeating FRB in the local Universe equals or exceeds the rates of all known catastrophic events: collapses, explosions or mergers of compact objects, including white dwarfs, neutron stars and black holes (Hashimoto et al. 2020). The actual rate of apparently non-repeating FRB must be greater than their measured rate, likely by a large factor, because some, perhaps the overwhelming majority, must be too faint to be detected as a result of beaming, insufficient radiated energy or a combination of these.

It is implausible that the distribution of fluxes or fluences cuts off at our detection threshold. The intrinsic cutoff of radiated flux density or energy implied if there is no undercount of more distant FRB (if all are above the detection threshold at their distances) would imply a cutoff in the flux or fluence distribution of closer FRB (where this emission cutoff would occur at fluxes or fluences far above the detection threshold). No such cutoff is observed. The true event rate must far exceed the observed rate.

This implies that apparently non-repeating FRB must either repeat or be emitted by sources not the product of catastrophic events. Plausible models associate them with ultra-magnetized neutron stars (“magnetars”), the results of catastrophic stellar collapse, likely in supernovae, that produce Soft Gamma Repeaters (SGR). This paper attempts to reconcile the the absence of a FRB associated with the giant outburst of SGR 1806–20 with the temporal and spatial association of FRB 200428 with lesser outbursts of SGR1935+2154, and attributes apparently non-repeating FRB to mini-SGR outbursts, perhaps of neutron stars with magnetic fields less than those of magnetars. This association is supported by similarities between the statistics of outbursts from a single SGR source and those of the bursts of FRB 200428. Apparently non-repeating FRB are too distant for their lesser bursts to be observed and their statistics measured.

2 EMPIRICAL BOUNDS ON REPETITION RATES
The definition of a non-catastropic burst model is one in which the mean rate of repetitions does not vary substantially between bursts; a single burst does not materially change the source’s properties. When many possible sources may be in a field of view, the time required to observe a burst in an initial survey is not an estimate of their repetition rate. Once a burst has been observed, its dispersion measure, which is
expected to be very stable, may permit unambiguous association with subsequent bursts (the rotation measure, although observed to vary somewhat in known repeaters, may be an additional source of discrimination). A quantitative test of the hypothesis of a constant rate of burst activity is suggested in Appendix A.

Direct observational bounds on repetitions of apparently non-repeating FRB are few. Ravi et al. (2019) found no repetitions in 78 hours of observation of FRB 190523 spread over 54 days, setting a 1σ upper limit on the detection rate at their threshold of $\lesssim 0.3/\text{d}$. FRB 190523 was only 15% over this threshold, so no information about the distribution of event sizes can be inferred from the absence of weaker bursts from this source.

Bannister et al. (2019) detected FRB 180924 in an 8.5 h ASKAP observing session. It had a fluence of 16 Jy-ms and a signal-to-noise ratio of 21, 2.1 times the minimum ratio of 10 (a fluence of 8 Jy-ms) usually taken in FRB astronomy as the threshold of reliable detection. They report no repetitions (or precursor bursts) in 720 hours of lower sensitivity observations with a threshold of 28 Jy-ms and no repetitions in 11 hours of higher sensitivity observations at Parkes with a threshold of 0.6 Jy-ms.

When different observing systems have differing sensitivities, their effective periods of observation must be corrected. If the distribution function of the source signal strength $F$ (flux or fluence) is $\propto F^{-\alpha}$, the actual duration $T_2$ of the second observation is replaced by an effective $T'_2 = T_2(F_2/F_1)^{-\alpha}$, where $F_2$ and $F_1$ are the detection thresholds, fluxes or fluences, of the second and discovery observations correspond to $\alpha$ non-repeating FRB like FRB 180924 is necessarily uncertain. The other. The applicability of these data to an apparently non-repeating FRB 121102. They also divided their data for the repeating FRB 121102. It had a fluence of 1.3 ms width of FRB 180924.

Zhang et al. (2021) fitted $\alpha \approx 1.85$ to their entire dataset for the repeating FRB 121102. They also divided their data into two subsets, finding $\alpha = 1.7$ in one and $\alpha = 2.6$ in the other. The applicability of these data to an apparently non-repeating FRB 180924 is necessarily uncertain. With $\alpha = 1.85$ the $T_2 = 720$ h of lower sensitivity (single dish) observations of Bannister et al. (2019) correspond to $T'_2 \approx 70$ h while their 11 h of higher sensitivity (Parkes) observations correspond to $T'_2 \approx 1500$ h. For the sensitive Parkes observations $\alpha = 1.7$ would imply $T'_2 \approx 1000$ h, while $\alpha = 2.6$ would imply $T'_2 \approx 10^3$ h. The absence of any detected bursts in these observations predicts with confidence $1-1/\beta$ a lower bound of $T'_2/\ln \beta$ on recurrence times of FRB 180924 at the strength of its initial (and so far only) detected outburst, or $\gtrsim 300$ h with 95% confidence. Recurrence times orders of magnitude longer (or infinite) are consistent with this limit, but not with the assumption that repeaters and apparent non-repeaters differ only in repetition rate.

The twice-daily revisits of the CHIME/FRB beam to points in its field of view, with typical exposures $\approx 15$ m, mean either that repetitions (at comparable or greater strength) of FRB it observes will be seen or that stringent upper bounds on their frequency will be established. CHIME/FRB’s apparent non-repeaters can be distinguished a priori from repeaters by some other property, such as “sad trombone” frequency drifts, then the absence of repetition of

$$N \approx 500 T/y \text{ sources in an observing time } T \text{ with duty factor } D \approx 30 \text{ m/1 d } \approx 2 \times 10^{-2} \text{ sets an upper limit to their repetition rate}$$

$$R \sim A^{C} \left( T \right)^{-2} \text{ (CHIME/FRB Collaboration 2020). One year of data can establish a repetition time } T \gtrsim 10 \text{y, while ten years may set a lower bound } \sim 10^3 \text{y, or detect repetitions if their characteristic rate is more than once per millenium. This limit or value would be inferred from the repetition of a single source or the absence of any repetitions in a database of many sources.}$$

3 OUTLIERS

A study (Katz 2021) of the energy distributions of astronomical objects and events showed that in almost all of them the most energetic object or event is statistically consistent with extrapolation of the observed power law distributions of lesser objects or events. When this is true, it is plausible that all the events are qualitatively similar, differing only in some continuous variable, usually energy scale.

There were only two exceptions: the distribution of gamma-ray fluences of outbursts of SGR 1806-20, and the distributions of fluxes and fluences of outbursts of FRB 200428. In both, the hypothesis of consistency could be rejected at a confidence level $> 99.9%$: In the case of FRB 200428 the power law exponent is uncertain because only three lesser bursts have been observed (Zhang et al. 2020; Kirsten et al. 2021), but the outlier, the MJy-ms discovery burst, is so extreme that its outlier nature cannot plausibly be doubted. This is entirely different from the statistics of known repeating FRB, whose brightest outbursts are consistent with the power laws fitted to their lesser outbursts.

This statistical observation is an argument for identifying objects like FRB 200428 with “magnetar” SGR, independent of its observed coincidence, temporal as well as spatial, with SGR 1935+2154. If FRB 200428 had been beyond 100 kpc (and within $\sim 12$ Mpc, so that its major outburst would have been detectable; CHIME/FRB Collaboration (2020)), it would have been classified as an apparently non-repeating FRB.

4 MODELS

Katz (2022) attributed known repeating FRB with detected event rates as high as $\sim 10^{-2}/$s (varying as a negative power of the detection threshold, again implying the absence of an intrinsic energy scale) to accretion discs or funnels around intermediate mass black holes. Any outbursts of such systems have no natural energy scale, and therefore must have a power law distribution, as in models of “self-organized criticality” (Katz 1986; Bak, Tang & Wiesenfeld 1987). Events without a characteristic scale must have a power law distribution because a break in the power law would define a characteristic scale, and conversely.

The absence of detected weaker repetitions of apparently non-repeating FRB suggests an association with SGR, the frequency of whose giant outbursts is not described by an extrapolation of the frequency distribution of lesser outbursts;
the giant outbursts are true outliers, qualitatively different from the lesser events (Katz 2021). This association is supported by the geometrical and temporal coincidence of FRB 200428 with an outburst of SGR 1935+2154 (Bochenek et al. 2020; CHIME/FRB Collaboration 2020; Li et al. 2020; Mereghetti et al. 2020; Ridnaia et al. 2020; Tavani et al. 2020). The fact that the few detected repetitions of FRB 200428 were four (Kirsten et al. 2021) to eight (Zhang et al. 2020) orders of magnitude fainter than its April 28, 2020 MJy·ms burst is consistent with the distribution of SGR outbursts (Göğüş et al. 2000; Hurley et al. 2005; Palmer et al. 2005; Göğüş et al. 2006; Golenetskii et al. 2007) but not with those of other repeating FRB.

5 DISCUSSION

No FRB was associated with the giant outburst of SGR 1806–20 (Tendulkar, Kaspi & Patel 2016). This is explicable because such giant outbursts fill the circumstellar space with opaque equilibrium pair plasma (Katz 1996) that would preclude the acceleration of relativistic particles required to emit FRB as well as the escape of coherent radio radiation. In equilibrium, a region the size of a neutron star fills with opaque pair plasma if $k_B T \gtrsim 22$ keV, a value only logarithmically dependent on the plasma dimensions. If such a plasma covers the surface of a neutron star its soft gamma-ray luminosity is $\gtrsim 10^{42}$ erg/s and expected to have a thermal spectrum. If the energy density is less than that corresponding to pair-black body equilibrium at 22 keV, equilibrium may not be achieved. A localized flare may also be smaller than the neutron star surface area. This is consistent with the non-thermal X-ray spectrum and peak power of $10^{30}$–$10^{41}$ erg/s of SGR 1935+2154 during the giant radio burst of FRB 200428 (Li et al. 2020; Mereghetti et al. 2020; Ridnaia et al. 2020; Tavani et al. 2020).

This paper predicts that SGR outbursts with luminosity $\gtrsim 10^{42}$ erg/s (like the giant outburst of SGR 1806–20) do not emit FRB while less luminous outbursts may, but do not necessarily, emit them. Apparently non-repeating FRB must be the products of less energetic “mini-SGR”, although to be detectable at cosmological distances their associated FRB must be orders of magnitude more energetic than FRB 200428.

It will be necessary to distinguish rarely repeating “true apparent non-repeaters” from “repeaters”. This may be possible on the basis of the distribution of intervals between bursts with fluxes within moderate (2–10) factors of each other and the ratios of brightest to second-brightest bursts. These ratios are $O(1)$ in known repeaters but $\gg 1$ in FRB 200428. The hypothesis of this paper and of the complementary Katz (2022) is that these ratios are bimodal.

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DATA AVAILABILITY

This theoretical study did not generate any new data.

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APPENDIX A: TESTING THE HYPOTHESIS OF CONSTANT RATES

If the direction of FRB 180924 had been identified before it was observed (for example, by the presence of some object of interest) the hypothesis of a constant mean repetition rate could be tested if sufficient data existed. This was not the case; it was observed in a single 8.5 hour observing run that was part of 12,000 hours of observation (Bannister et al. 2019). The following procedure might be useful when a prior knowledge of the object exists. It is not useful here because the effective observing time $T_1$ is the entire 12,000 hours of the survey; to show its potential utility the inapplicable $T_1 = 8.5$ h of the single observing run in which FRB 180924i was observed is used in the numerical estimates.

If one and only one burst is observed in an observing time $T_1$, repetition rates $r < 1/(\beta T_1)$ for $\beta \gg 1$ may be excluded with confidence $\approx 1 – 1/\beta$. The probability of no burst in an independent observation of duration $T_2$ is then $\exp(-rT_2) < \exp[\beta(T_2/T_1)]$. The absence of a burst would reject the constant repetition rate hypothesis at a level of confidence $\gamma = 1 – \exp(-rT_2)$. Setting $\gamma = \beta$ indicates that the duration of observation required to reject the constant
rate hypothesis is
\[ T_2 = T_1 \beta \ln \beta. \]  
(A1)

Rejection at the 95% confidence level (\( \beta = 20 \)) requires \( T_2 > 60T_1 \).

When different observing systems have differing sensitivities, \( T_2 \) is replaced by an effective \( T'_2 = T_2 (F_2/F_1)^{-\alpha} \), where \( F_2 \) and \( F_1 \) are the detection thresholds, fluxes or fluences, of the two systems and the distribution function of the source signals is assumed to be \( \propto F^{-\alpha} \); for FRB \( \alpha \approx 1.85 \) (Zhang et al. 2021) is plausible, although it appears to be variable. With this scaling, the 720 hours of lower sensitivity observations of Bannister et al. (2019) have \( T'_2 \approx 70 \) h while their 11 h of higher sensitivity observations have \( T'_2 \approx 1500 \) h, implying \( T'_2/T_1 \approx 170 \). This is sufficient, given the assumptions (most significantly, the energy distribution of the bursts), to exclude the constant rate hypothesis with a confidence level > 97%. Zhang et al. (2021) suggest \( \alpha \approx 1.7 \) in one subset of their data and \( \alpha = 2.6 \) in another subset. The lower value would imply (for the Parkes data) \( T'_2 \approx 1000 \) h, \( T'_2/T_1 \approx 115 \) and rejection of the constant rate hypothesis at a confidence level \( \approx 97\% \); the higher value of \( \alpha \) would increase \( T'_2/T_1 \) to \( 10^2 \) and rejection to a confidence level > 99\%\(^2\).

\[^2\] Let us not forget Ehrenfest’s admonition (Goudsmit 1963) “If it is essential to use probability to prove that you are right, you are usually wrong.”