A FRB in a Globular Cluster: Why Is This Neutron Star Different From (Almost) All Other Neutron Stars?

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ABSTRACT
Most Fast Radio Burst (FRB) models are built from comparatively common astronomical objects: neutron stars, black holes and supernova remnants. Yet FRB sources are rare, and most of these objects, found in the Galaxy, do not make FRB. Special and rare circumstances may be required for these common objects to be sources of FRB. The recent discovery of a repeating FRB in a globular cluster belonging to the galaxy M81 suggests a model involving a neutron star and a close binary companion, likely a white dwarf; both neutron stars and close binaries are superabundant in globular clusters. Magnetic interaction is a plausible, though unproven, mechanism of acceleration of relativistic particles that may radiate coherently as FRB. In such a model the energy source is the orbital kinetic energy, and not limited by the magnetostatic energy of a neutron star. Double neutron star binaries cannot be the observed long-lived repeating FRB sources, but might make much shorter lived sources, and perhaps non-repeating FRB.

Key words: radio continuum, transients: fast radio bursts, stars: neutron, stars: binary

1 INTRODUCTION
The localization (Kirsten et al. 2021) of FRB 20200120E to a globular cluster in the galaxy M81 is an important clue to the origin and mechanism of FRB. It has long been known (Clark 1975; Katz 1975) that Galactic globular clusters are superabundant in neutron star binary X-ray sources. They also contain many “recycled” pulsars with decayed magnetic fields, spun up to millisecond periods by accretion from close binary companions (Srinivasan 2010). Some of these companions have survived in bound orbits but others appear to have dissipated.

Neutron stars are natural components of any model of FRB because of their large magnetic fields, high-brightness coherent emission as pulsars, and compact size, and soft gamma repeaters (SGR) have been suggested as their sources by many (Katz 2018). But there are a large number of neutron stars and dozens of SGR in the Galaxy, and to date only one has been the source of a FRB (or a FRB-like event, FRB 200428, orders of magnitude less energetic than “cosmological” FRB): SGR 1935+2154 (Bochenek et al. 2020b; CHIME/FRB Collaboration 2020b; Li et al. 2020; Mereghetti et al. 2020; Ridnaia et al. 2020; Tavani et al. 2020).

This is evidence that “ordinary” neutron stars are not the principal source of FRB (Katz 2020a); if neutron stars make FRB, those that do, either directly as super-giant pulsar pulses, indirectly as stimulants of surrounding supernova remnants or in some other manner, must be distinguished in some way from other neutron stars. The distinction must be based on more than magnetic field or rotation rate, because the Galaxy contains many neutron stars that don’t make FRB but fill those parameter spaces. Age might be relevant; FRB 121102 may be surrounded by a very young, dense, rapidly changing and strongly magnetized supernova remnant (SNR) with varying dispersion measure (DM) and rotation measure (RM) (Katz 2021a), but other FRB do not appear to be embedded in dense, strongly magnetized plasma, and show no evidence of a near-source contribution to either DM or RM.

How may the globular cluster environment naturally produce a rare subclass of neutron stars that plausibly, or at least possibly, make FRB in a manner that other neutron stars do not? How does this subclass differ from the more numerous globular cluster neutron stars that do not make FRB? Here I outline some fragmentary ideas that address these questions. They are based on the hypothesis that an interacting binary is an environment favorable for making FRB. As with other FRB models (Platts et al. 2019), I attempt only to show the possibility of emitting the observed FRB; the failure to explain radio emission of pulsars 54 years after their discovery shows the difficulty of understanding coherent emission processes.

2 HOW GLOBULAR CLUSTERS ARE SPECIAL
Globular clusters are superabundant in neutron stars, and in close neutron star binaries (some of which are no longer binaries, as the nondegenerate companions have been dissipated by accretion and excretion). This is the result of the clusters’ high stellar densities (Pooley et al. 2003).

It is necessary to find circumstances that distinguish a few,
rare, neutron stars from the many other neutron stars in globular clusters that are low mass X-ray binaries, recycled pulsars or entirely inactive. Presence in an asynchronous binary system implies interaction, in analogy to the Jupiter-Io interaction, and at least the possibility of particle acceleration and coherent emission (Mottez & Zarka 2014; Mottez, Zarka & Voisin 2020). The requirement that the model occur rarely, while consisting of common ingredients, points to a short lifetime in its active (FRB-emitting) phase.

These conditions may be satisfied by a model in which a young neutron star with a large magnetic moment $\mu \sim 10^{33}$ Gauss-cm$^3$ interacts magnetically with a close binary companion. The low magnetic moments of recycled pulsars in globular clusters are attributed to field decay at their presupernova ages, and do not exclude the possibility of birth with fields $B \sim 10^{15}$ G as large as those of SGR. In considering exceptional objects low, but non-zero, ongoing rates of neutron star formation by merger of double white dwarf binaries may be considered.

A feature of a FRB model involving a binary neutron star is that the orbital kinetic energy, equal to the orbital gravitational binding energy, may be available to power FRB emission. This may satisfy the energy requirements of $10^{47}$–$10^{49}$ ergs (Margalit, Metzger & Sironi 2020) that exceed the magnetostatic energies $\sim 10^{47}$ ergs of even the most strongly magnetized known neutron stars, even apart from the unknown efficiency of tapping magnetostatic energy.

3 PARAMETERS

The lifetime of a close binary, limited by its emission of gravitational radiation, which, assuming constant masses (no mass transfer, the companion not overflowing its Roche lobe) is

$$t_{GR} = \frac{5 \, c^5}{256 \, G^3 \, M_1 \, M_2 (M_1 + M_2)} \frac{R^4}{\epsilon_3},$$

(1)

where $R$ is the separation of the stars and $M_1$ and $M_2$ their masses. Only a degenerate companion is compact enough to permit a small $R$ and a short $t_{GR}$ in the binary’s active phase as a FRB source. The evolution of close neutron star-white dwarf binaries has recently been discussed by Chen et al. (2021).

In order that a neutron star-white dwarf binary evolve to separations small enough that interaction is possible, it must be formed with $R$ small enough that $t_{GR}$ is less than the age of the Galaxy; Eq. 1 implies that this requires the initial separation $R \lesssim 2 \times 10^{13}$ cm. A tighter constraint is imposed by the requirement that $t_{GR}$ be less than the decay time of the neutron star’s magnetic field; this time scale is uncertain, but Viganò et al. (2013) indicate values of $10^5$–$10^6$ y, which would require $R \lesssim 2 \times 10^{10}$ cm. Three-body encounters among stars with speeds $\mathcal{O}(v_{rms})^2$, where $v_{rms} \approx 20$ km/s is a globular cluster’s escape speed, produce binaries with $R \sim GM_2/v_{rms}^2 \sim 3 \times 10^{13}$ cm. Suitable binaries can only be produced by tidal captures or collisions, in which a neutron star passes close to (or enters the envelope of) a main sequence star that later evolves to a white dwarf.

The need to keep $R$ small and minimize $t_{GR}$ to make the systems rare, while requiring that $t_{GR}$ not be less than observed repeating FRB source lifetimes, pins $R$ when the binary is an active FRB emitter in the range

$$1.3 \times 10^9 \text{ cm} < R \lesssim 5 \times 10^9 \text{ cm},$$

(2)

where we have adopted $M_1 = 1.4M_\odot$ for the neutron star and $M_2 = 0.7M_\odot$ for a white dwarf companion. The steep dependence of $t_{GR}$ on $R$ (Eq. 1) and of the interaction energy $E$ on $R$ (Eq. 7) reduce the uncertainty of the upper bound, while $t_{GR} > 8$ y (FRB 121102) gives the firm lower bound (weakly dependent on the assumed masses).

The gravitational radiation lifetime is related to the orbital period

$$P_{orb} = 2\pi \sqrt{\frac{R^3}{G(M_1 + M_2)}},$$

(3)

by

$$P_{orb} = 2\pi t_{GR}^{3/8} \left( \frac{256G^{5/3}M_1 M_2}{5c^3 (M_1 + M_2)^{1/3}} \right)^{3/8} = 18.5 \left( \frac{t_{GR}}{10 \text{ y}} \right)^{3/8} \text{s.}$$

(4)

The orbital separation $R$ may be restated in terms of $t_{GR}$

$$R = 1.34 \times 10^9 \left( \frac{t_{GR}}{10 \text{ y}} \right)^{1/4} \text{ cm.}$$

(5)

For the assumed mass ratio, the radius of the Roche lobe of the less massive companion $R_{WD} \approx 0.3R$. Taking $R_{WD} = 7 \times 10^6$ cm increases the lower bound to $R > 2.3 \times 10^9$ cm and $P_{orb} > 40$ s. If the white dwarf is semi-detached these lower bounds are approximate values of the parameters. It may be only a coincidence, but this $P_{orb}$ is close to the peak (60 s) of the distribution of burst intervals during an active phase of FRB 121102 (Katz 2019).

For these parameters the gravitational radiation lifetime of the orbit is, very approximately,

$$t_{GR} \sim 100 \text{ y.}$$

(6)

$t_{GR}$ is much longer for less massive white dwarfs because $t_{GR} \propto R^3/M_2$; their larger $R_{WD}$ and smaller $R_{WD}/R$ would imply greater $R$. The model does not predict a measurably short life expectancy. Perhaps FRB activity gradually declines on the time scale $t_{GR}$ as the white dwarf loses mass and $R$ increases. A rough scaling, using the mass-radius relation $R_{WD} \propto M_2^{-1/3}$ for low mass white dwarfs and $R \sim R_{Roche}(M_1/M_2)^{1/3} \sim R_{WD}(M_1/M_2)^{1/3} \propto M_2^{-2/3}$ is

$$t_{GR} \propto R^{11/2} \propto M_2^{-11/3}.$$
4.1 Slowly rotating neutron star, non-magnetized white dwarf

The energy density of a neutron star’s magnetic field at its companion is \( \sim \mu^2 / (8\pi R^6) \), where \( \mu \) is the neutron star’s magnetic moment. The magnetostatic energy associated with interaction with an unmagnetized companion of radius \( R_c \) is

\[
\mathcal{E} \sim \frac{B^2}{8\pi} \frac{4\pi}{3} R^3_c \sim \frac{\mu^2 R^3_c}{6R^6_c} \sim 4 \times 10^{35} \mu^2_{33} \text{ ergs,}
\]

where the numerical value assumes a Roche lobe filling companion with \( R_c = 7 \times 10^6 \text{ cm} = 0.3R \), appropriate to the assumed parameters of a NS-WD binary system, and \( \mu_{33} \equiv \mu / 10^{33} \text{ G-cm}^3 \).

4.2 Slowly rotating neutron star, magnetized white dwarf

If the white dwarf is strongly magnetized, with moment \( \mu_{WD} \), then Eq. 7 is replaced by

\[
\mathcal{E} \sim \frac{\mu_{WD}^2 R^3_{WD}}{R^6} \sim 10^{38} \mu_{33} \mu_{WD} R_{WD} D_3 \text{ ergs,}
\]

where \( \mu_{WD33} = \mu_{WD} / 10^{33} \text{ G-cm}^3 \). While the largest known neutron star \( \mu_{33} \sim 1 \), white dwarfs are known with \( \mu_{WD33} \) as large as \( \sim 100 \) (Ferrario, de Martino & Gansicke 2015), permitting \( \mathcal{E} \sim 10^{40} \text{ ergs} \). The pairing of a strongly magnetic neutron star with a strongly magnetic white dwarf is likely to be rare, but so are FRB sources.

4.3 Rapidly rotating neutron star

If the neutron star has an angular rotation rate \( \omega > 2\pi c / R \) and spin period \( P_{\text{spin}} = 2\pi / \omega \) then the companion is in its radiation zone, the interaction is not magnetostatic, and Eq. 7 is replaced by

\[
\mathcal{E} \sim \frac{2}{9} \frac{\mu^2 R^3}{R^6} \left( \frac{\omega}{c} \right)^4 \sim 5 \times 10^{35} \mu_{33}^2 \text{ ergs.}
\]

The requirement that the spindown age be \( > 8 \text{ y} \) (requiring that the model describe FRB 121102, and perhaps all repeating FRB) then implies \( P_{\text{spin}} > 0.5 \mu_{33} \text{ s} \) and

\[
\mathcal{E} \sim \frac{2}{9} \frac{\mu^2 R^3}{R^6 c^2} \left( \frac{2\pi}{P_{\text{spin}}} \right)^4 \sim 5 \times 10^{35} \mu_{33}^{-2} \text{ ergs.}
\]

This energy can be much greater than that of Eq. 7 if \( \mu_{33} \ll 1 \). Its maximum value is given by Eqs. 9, 10 if \( \omega \sim 10^3 / \text{s} \), the fastest a neutron star can spin, and \( \mu_{33} \sim 10^{-3} \), the greatest \( \mu_{33} \) permitted by an eight year lifetime for such a fast-spinning neutron star, and is \( \mathcal{E} \sim 5 \times 10^{41} \text{ ergs} \). As for strongly magnetized but slowly rotating neutron stars interacting with strongly magnetized white dwarfs (Eq. 8), it posits an unprecedented object, a very young millisecond neutron star with a typical pulsar field \( B \sim 10^{12} \text{ G} \). This is consistent with the rarity of FRB sources.

4.4 Comparison to known Galactic objects

The proposed models have much larger \( \mu \) and smaller \( R \) than known Galactic binary millisecond pulsars and close double white dwarfs. As a result, \( \mathcal{E} \) (Eqs. 7, 8, 9) is greater by many orders of magnitude, explaining why the models predict that these binaries do not radiate observable FRB, even though they are much closer than M81.

4.5 Dissipation

There is no first-principles theory of how this energy may be dissipated and radiated. The neutron star’s magnetic field interacts with the companion star, perhaps drawn into the companion’s surface layers if they are convecting, or into a mass-transfer flow if the companion fills its Roche lobe. Dissipation by magnetic reconnection may require that the neutron star’s rotation be asynchronous with the orbital period, as are known neutron star binaries.

In SGR the entire magnetosphere appears to relax during giant outbursts (Katz 1982), and the energy density is so high that the released energy must thermalize into a near-equilibrium pair-photon fireball with a thermal spectrum (Katz 1996). At the lower energy densities of FRB coherent radiation by relativistic particles may occur, in analogy with pulsars. However, the extreme ratios of FRB energies to those of pulsar giant pulses indicate that FRB cannot be explained as an extrapolation of observed pulsar giant pulses (Bera & Chengalur 2019). They are outliers, indicating a qualitatively different origin (Katz 2021b).

5 NUMBERS OF SOURCES

I first estimate the expected number of FRB sources in the assumed model at redshifts \( z \leq 1 \), even though the FRB discovered in a globular cluster (Kirsten et al. 2021) is in M81 at a distance of 3.6 Mpc, about 1000 times closer than \( z = 1 \). The cross-section for one star to approach another within a distance \( R \) (at which dissipation may bind it gravitationally) is

\[
\sigma \approx \pi \frac{G M R}{v_{\infty}^2} \sim 2 \times 10^{27} \text{ cm}^2, \tag{11}
\]

where \( M \) is the sum of the masses (taken to be \( 2 1.4 M_\odot \)), \( v_{\infty} \approx 20 \text{ km/s} \) is a typical globular cluster virial or escape velocity, I have taken \( R \sim 10^{15} \text{ cm} \) for capture into a common envelope by a red giant that will evolve into a white dwarf, and strong gravitational focusing (\( v_{\infty} \ll \sqrt{GM/R} \)) has been assumed. Direct captures by white dwarfs are less frequent because of their small radii.

If there are \( N \) neutron stars in a cluster, all in its densest central regions (as expected from gravitational relaxation) where stellar density is \( n \), \( N_\odot \) major (mass \( \sim M^* \)) galaxies with \( z \leq 1 \), \( N_{GC} \) such globular clusters per galaxy, and the captured tightly bound neutron stars are active FRB sources for a time \( t_{\text{FRB}} \), then the total number of active FRB sources in the Universe is

\[
N_{\text{FRB}} = \sigma v_{\infty} N_G N_N N_{GC} t_{\text{FRB}} \sim 10^4, \tag{12}
\]

where we have taken \( N_G = 10^9 \) (Conselice et al. 2016), \( N = 10^4 \), the red giant density \( n = 10^{-53} \text{ cm}^{-3} \) \( (300/\text{pc})^3 \), \( N_{GC} = 100 \) and \( t_{\text{FRB}} = 100 \text{ y} \). This number is uncomfortably low, but \( t_{\text{FRB}} \) could be one or more orders of magnitude greater; estimated decay times of neutron star magnetic fields (Viganò et al. 2013) are three or four orders of magnitude greater than the \( t_{\text{FRB}} \) assumed here, with a proportional increase in \( N_{\text{FRB}} \).

The price paid for assuming a larger \( t_{\text{FRB}} \) is a larger \( R \) and smaller \( \mathcal{E} \). This problem is mitigated if FRB are collimated into a solid angle \( \Omega \), reducing the energy per burst by the factor \( \Omega/4\pi \). The burst rate must be correspondingly increased.
but it is not strongly constrained (it may be limited by the time required to restore a tangled metastable field configuration, plausibly the neutron star’s rotation period). As in most FRB models, the instantaneous power, not the mean power, is the energetic constraint; collimation can reduce the inferred instantaneous power by a large factor, but does not affect the inferred mean power if the beam is isotropically distributed on the sky.

FRB 20200120E poses a special problem because in Eq. 12 $N_C$ must be replaced by the number of galaxies within about $3.6 \times 10^5$ Mpc, the distance within which 1/f of the galaxies are as close to us as M81, or closer, so that the hypothesis that M81 is a random accident cannot be rejected at a confidence level $> 1.3$. Taking $f = 10$, and ignoring the selection effect that closer FRB are more likely to be observed, $N_C$ is replaced by $\sim 300$ (the density of galaxies in the Local Group is much greater than their mean cosmological density) and $N_{FRB < 3Mpc} \sim 10^{-4}$, apparently inconsistent with the observation of FRB 20200120E. This may be resolved because the bursts of FRB 20200120E had fluxes and fluences comparable to those of typical cosmological FRB, yet its proximity implies that they were about $10^9$ times less energetic. This permits larger values of $R$ and $t_{FRB}$ longer by several orders of magnitude (just how many depends on which of the models of Sec. 4 is adopted). The processes that create possible neutron star sources in globular clusters have recently been discussed by Kremer, Piro & Li (2021); Lu, Beniamini & Kumar (2021).

6 DISTRIBUTION OF BURST INTERVALS

A source that emits in stochastically wandering directions, but with a rotationally modulated anisotropic likelihood (mean beam pattern), displays a wide distribution of burst intervals that peaks at its rotation period although the bursts are not strictly periodic (Katz 2019). The absence of strict periodicity (Zhang et al. 2018; Li et al. 2021) in FRB 121102 is evidence in favor of rotational modulation of stochastically directed emission. It cannot (by itself) distinguish between stochastic wandering of the direction of beamed emission (Katz 2017) and temporarily stochastic emission of isotropic radiation. However, isotropic emission models place much more severe demands on the instantaneous radiated power and energetics, which is an argument in favor of wandering beams.

7 PERIODIC MODULATION?

Two repeating FRB sources (FRB 20180916B (CHIME/FRB Collaboration 2020a; Pastor-Marazuela et al. 2020; Pilia et al. 2020; Pleunis et al. 2020) and FRB 121102 (Rajwade et al. 2020; Cruces et al. 2021)) show activity modulated with periods of 16.35 d and $\approx 160$ d, respectively. It is not known if this behavior is universal among repeating FRB or is particular to some fraction of them; these two sources are well-observed, and therefore selection favored detection of such periods in them over other, less well observed, repeating FRB, even if the behavior is universal.

Several models of this behavior may be considered in the context of the present model of FRB:

(i) Precession of the orbital plane of the neutron star-white dwarf binary, driven by a third, more distant, companion. If all three masses are comparable, then the period of the outer orbit is roughly the geometric mean of the orbital period of the close binary and the precession period:

$$P_{3rd \ body} \sim \sqrt{P_{orb} P_{precess}} \sim 1-10 \text{ d.}$$

There is no evident means of detecting the third body directly. If $P_{orb}$ or the neutron star’s spin period were detected, the presence of the third body might produce a measurable Doppler shift.

(ii) If the neutron star’s rotation is synchronous with its orbital period, its orientation may oscillate in phase with a frequency

$$\omega_{osc} \sim \sqrt{\omega/I},$$

where $I$ is the neutron star’s moment of inertia (Joss, Katz & Rappaport 1979). For $E$ given by Eq. 7 $\omega_{osc} \approx 10^{-3} \mu_{33}/s$. roughly consistent with the observed periods of SGR 20180916B and SGR 121102. However, for the much larger values of $E$ given by Eqs. 8 and 10, that more readily explain FRB energetics, $\omega_{osc}$ is much too large to be consistent with the observed periods.

(iii) If the neutron star is rotating at a frequency $\omega_r$ then its rotation axis will precess as a result of the torque exerted by the companion on its rotational equatorial bulge. The precession frequency (if $M_{WD} \sim M_{NS}$)

$$\omega_{pre} \sim \frac{M_{WD} R_{NS}^3}{I R^2} \omega_r \sim \frac{M_{WD}}{M_{NS}} \left(\frac{r_{NS}}{R}\right)^3 \omega_r \lesssim 10^{-10} \omega_r,$$

which is too slow to explain the observed periodicities for plausible values of the parameters.

8 FUTURE BEHAVIOR

If the binary is detached, then as gravitational radiation brings the stars together their interaction will become stronger and FRB activity may gradually increase on a time scale $\sim t_{GR}$. This inference is uncertain because it ignores any effect of possible changes in the neutron star’s rotation period. Dissipation may synchronize the neutron star’s rotation to the orbital period, as happens to white dwarfs in polars (Joss, Katz & Rappaport 1979), ending dissipation and likely terminating FRB activity.

The evolution of semi-detached binaries, with the white dwarf losing mass to the neutron star, is discussed by van Haften et al. (2011); Bobrick et al. (2017); Zenati et al. (2020); Bobrick et al. (2021); Yu et al. (2021). If the white dwarf is much less massive, mass transfer may occur on the slow time scale $t_{GR}$, as in recycled and “black widow” pulsars. As the white dwarf loses mass $R_e \approx R_{WD} \propto M_{WD}^{-1/3}$ and $R \propto M_{WD}^{-2/3}$, so the interaction energy will decay on a time scale $\sim t_{GR}$. If the neutron star’s rotation is not already synchronous, synchronization may accelerate the decay of activity. However, many such binaries are known in the Galaxy, and they do not emit FRB. Neutron star binaries with more massive white dwarf companions are not known, and may have very short lifetimes terminated by dynamical mass transfer, a burst of gravitational waves, and a possible SN-like event or collapse to a black hole. Such a process...
would last much longer (seconds, and perhaps orders of magnitude longer) than the ms duration of non-repeating FRB, but might explain non-repetition.

9 DISCUSSION

Explanation of repeating FRB in this model must reconcile the energies of Eqs. 7, 8, 10 with FRB energetics. Gajjar et al. (2018) report bursts of FRB 121102 with fluences up to ~ 1 Jy-ms. At its redshift of 0.193 this corresponds to an isotropic-equivalent energy $E_{iso} \sim 10^{39}$ ergs, much greater than the interaction energy of Eq. 7, and uncomfortably close to the much greater interaction energies of Eqs. 8, 10. Even if a FRB is associated with a global relaxation of the magnetic field in the interaction region of size $\sim R_c$, the observed FRB fluences are possible only if their radiation is narrowly collimated. The arguments for collimation of FRB emission (Katz 2018, 2019, 2020b) occur in all models of repeating FRB.

In the simplest possible model of beamed radiation the FRB source emits continuously, but its beam wanders on the sky (Katz 2017). If it is observed to have a duty factor $D$ by an unfavored observer (excluding the possibility that the beam is preferentially directed towards the observer), its solid angle of emission $\Omega \sim 4\pi D$ sterad. For FRB 121102 $D \sim 2 \times 10^{-6}$ (Katz 2019). $\Omega \sim 2 \times 10^{-5}$ sterad, implying a Lorentz factor of the emitting charge bunches $\gamma \geq 200$, consistent with other constraints (Katz 2020b) and with relativistic kinematics with the assumed Lorentz factor (Katz 2019).

The required radiated burst energy $E \sim (\Omega/4\pi)E_{iso} \sim DE_{iso} \sim 10^{35}$ ergs. This is consistent with the interaction energies Eqs. 7, 8, 10, provided the magnetic field in the interaction region can relax on the ms time scale of the FRB and radiate coherently into a collimated beam, with its duration shortened from $R_c/c \sim 25$ ms to the observed $\sim 1$ ms.

The slowly rotating model with an unmagnetized companion requires an efficiency of coherent emission of $\sim 1\%$ (Eq. 7), but the magnetized companion and fast rotating models only require $\gamma \sim 10^{10}$--$10^{11}$ for their most favorable parameters. Pulsars turn spindown energy into coherent emission with greater efficiency.

If the companion were a neutron star (Totani 2013; Wang et al. 2016; Dokuchaev & Erosenko 2017), $E$ would be several orders of magnitude less than for a WD companion unless $R$ were $\sim 10$--$100$ times smaller than assumed here (Eq. 2). Such a small $R$ would imply $t_{GR} \sim 10^4$--$10^8$ times less, $\ll 1$ y, inconsistent with the observed lifetimes of repeating FRB. It would be consistent with non-repeating FRB or yet-unobserved very short-lived (minutes--days) repeating FRB. The hypothesis that non-repeaters are close NS-NS binaries while repeaters are more distant NS-WD binaries might explain the bimodal distribution of the duty factor $D$ (Katz 2017, 2018, 2019), with upper bounds for apparently non-repeating FRB several orders of magnitude less than the values observed for repeaters. Then non-repeaters would be associated with merging neutron stars, kilonovae and gravitational wave events. Testing that association would require large solid-angle or all-sky sensitivity to FRB, such as provided by STARE2 (Bochenek et al. 2020a) or the proposed lunar FRB scattering observatory (Katz 2020c), unfortunately at less sensitivity than a high-gain focussing telescope. The likelihood that FRB are narrowly collimated means that the failure to observe a FRB coincident with a gravitational wave event would not disprove the hypothesis.

10 DATA AVAILABILITY

This theoretical study did not generate any new data.

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