Are Fast Radio Bursts Made By Neutron Stars?

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\textbf{ABSTRACT}

Popular models of repeating Fast Radio Bursts (and perhaps of all Fast Radio Bursts) involve neutron stars because of their high rotational or magnetostatic energy densities. These models take one of two forms: giant but rare pulsar-like pulses like those of Rotating RAdio Transients, and outbursts like those of Soft Gamma Repeaters. Here I collate the evidence, recently strengthened, against these models, including the absence of Galactic micro-FRB, and attribute the 16 day periodicity of FRB 180916.J0158+65 to the precession of a jet produced by a massive black hole’s accretion disc.

\textbf{Key words:} radio continuum: transients, stars: neutron, (transients:) fast radio bursts, stars: black holes

\section{INTRODUCTION}

The sources and mechanisms of Fast Radio Bursts (FRB) are one of the most prominent mysteries of modern astronomy. Most models involve neutron stars to take advantage of their deep gravitational potential wells, the great magnetostatic and rotational energies of some neutron stars and their other known transient emissions. Pulsar-like models provide a natural analogy to the coherent emission of FRB. Magnetostatic energy (“magnetar”) models of Soft Gamma Repeaters (SGR) readily provide the energies of FRB, as may neutron star accretional models involving the release of gravitational energy. Although many models of pulsars and magnetars have been developed, none of them led to a prediction of FRB, as might have been expected were FRB their natural consequence. These models require very large extrapolations, quantitative (in energy) or qualitative (in the type of emission) to account for FRB, which suggests re-examination of the assumption that neutron stars are responsible.

Neutron star models have difficulty explaining repeating FRB because the well-studied repeating FRB 121102 is not periodic (Zhang \textit{et al.} 2018). Magnetic fields are essential to pulsar and “magnetar” SGR models of FRB. Magnetic fields vary with direction from their source, as will any radiation related to the field. Unless a rotationally aligned dipole, rotation sweeps the angular distribution of radiation emitted near the neutron star across the observer, leading to an observed periodic modulation or recurrence at integral multiples of an underlying period, whatever the radiation mechanism. Examples include pulsars, Rotating RAdio Transients (RRAT), SGR and Anomalous X-Ray Pulsars (AXP, the quiescent phase of SGR).

Radiation energized by a neutron star’s rotationally swept fields or particles may be emitted far away, perhaps in a wind nebula or supernova remnant. Brief bursts, like FRB, emitted by interaction with distant small structures would also be rotationally modulated, although continuous emission need not be.

These difficulties arise in any neutron star model that involves a magnetic field: pulsar-like, SGR-like and accretional models in which a magnetic field channels accretion. They apply also to apparently non-repeating FRB if they are, as suggested but unproven, repeaters whose repetitions have not been observed because of their infrequency (James \textit{et al.} 2019) or insufficient observational coverage.

FRB were reviewed by Katz (2016a, 2018a); Cordes \& Chatterjee (2019); Petroff, Hessels \& Lorimer (2019); Platts \textit{et al.} (2019) provides a complete and updated catalogue of proposed models. The argument of the preceding paragraphs is not universally accepted, and neutron star models remain popular. It is a strong argument against pulsar-like models, whose rotation implies bursts separated by integer multiples of a rotation period. It is a somewhat weaker argument against SGR-like models in which it only implies periodic modulation of the observed strengths and frequencies of bursts. Although AXP are periodically modulated and longer SGR outbursts show periodic substructure, rotational modulation of the timing of detected brief SGR outbursts is not evident.

The purpose of this note is to synthesize the theoretical and observational arguments against any neutron star origin of FRB. I pay particular attention to the new upper bounds on MeV gamma-ray emission of two repeating FRB found by Casentini \textit{et al.} (2019) that provide additional evidence against SGR-like models.
2 PULSAR-LIKE MODELS OF FRB

In these models FRB are produced by the same mechanisms as radio pulsars, but with much higher energies and with most pulses nulled; they would be more energetic analogues of RRAT. Such models imply pulse intervals that are integer multiples of a neutron star’s rotation period. This appears to be inconsistent both with older data (Hardy et al. 2017; Scholz et al. 2017) and with a series of 93 bursts observed in one five-hour observing run of the repeater FRB 121102 (Zhang et al. 2018).

Such a run is short enough that plausible period derivatives do not break the requirement that burst separations be integer multiples of a single period. Timing of bursts separated by gaps longer than a few hours cannot constrain short (ms) periods because plausible period derivatives make the cycle count ambiguous, although the different short periods derived from different runs must be consistent with plausible spindown rates. Intervals between bursts in widely separated runs can constrain longer periods, but these have been excluded for FRB 121102 on the basis of the multiple intervals observed in a single run; see discussions in Katz (2018b, 2019).

Energetics are an additional problem for pulsar-like models. The usual assumption that pulsars have no energy reservoir between their rotational energy, tapped at the rate of dipole radiation, and a relativistic wind and radiation field, implies extreme values of both magnetic dipole moment and rotation rate in order to explain FRB powers $\sim 10^{45}$ erg/s. This combination may be impossible, and would imply very short lifetimes (Katz 2016a, 2018a).

There are two possible loopholes to the energetic argument: If FRB are narrowly collimated (Katz 2017a,b) their power requirements would be correspondingly relaxed. If pulsar magnetospheres contain an intermediate energy reservoir, such as might be provided by transitions (Katz 2017c) between the magnetospheric states of intermittent pulsars (Kramer et al. 2006) whose spindown rates differ by tens of percent and pulse powers by orders of magnitude, their dipole moment and spin rate would be essentially unconstrained. Both these loopholes are speculative, and there is no evident path to closing them.

3 SGR-LIKE MODELS OF FRB

SGR-like models are attractive because of their abundant energy; the giant outburst of SGR1806-20 on December 27, 2004 released about $10^{47}$ ergs in about 0.1 s (Hurley et al. 2005; Palmer et al. 2005). This is about seven orders of magnitude greater than energies inferred for FRB (Thornton et al. 2013), and the ratio is even larger if FRB are collimated, as is plausible for coherent radiation by relativistic particles. In addition, SGR have sub-ms rise times (see discussion in Katz 2016b), consistent with the ∼ ms durations of FRB and shorter than any other known astronomical process other than pulsar pulses and their substructure.

3.1 Theoretical difficulties

Here I consider issues that arise if FRB are produced by relativistic electrons near the surfaces of neutron stars around the peaks of SGR outbursts. SGR appear to be thermalized sources with approximately black-body spectra at temperatures of tens or hundreds of keV, while FRB are produced by coherent non-thermal processes with brightness temperatures as high as $\sim 10^{35}$ K. In general, uncollimated radiation intensities $\gtrsim 10^{29}$ ergs/(cm$^2$ s), about $10^{-6}$ of the intensity of SGR 1806-20 at a neutron star radius, rapidly thermalize into equilibrium photon-pair plasma (Katz 1996). The spectral data on SGR are averaged over their ∼ 0.1 s durations and may not constrain their spectra during their sub-ms rise or at other times when their luminosity is low, so these issues may not arise if FRB are emitted when the SGR luminosity is below its peak.

The radiation environment of a SGR during the peak of its outburst is hostile to relativistic particles, such as required in many models to radiate a FRB. Particles radiating curvature radiation$^1$ at a frequency $\nu$ in a magnetic field with radius of curvature $R$ have Lorentz factors

$$\gamma \sim \left(\frac{\nu R}{c}\right)^{1/3} \sim 50,$$

where we have taken $\nu \sim 1$ GHz and $R \sim 10^6$ cm, appropriate to neutron star models of FRB. A relativistic electron of energy $E = \gamma m_e c^2$ moving through a thermal uncollimated radiation field of energy density $\mathcal{E}$ suffers an energy loss by Compton scattering

$$\frac{dE}{dt} \sim \gamma^2 \sigma \mathcal{E},$$

where $\mathcal{E}$ measures its path and $\sigma$ is the Compton energy loss scattering cross-section (the Klein-Nishina cross-section convolved with the kinematics of recoil energy loss)

$$\sigma \sim \left(\frac{\nu^2}{m_e c^2}\right)^2 \frac{\ln(E_p/m_e c^2)}{E_p/m_e c^2} \sim \left(\frac{\nu}{m_e c}\right)^2 \frac{\ln \gamma}{\gamma},$$

where $E_p$ is the photon energy in the electron’s frame. The final approximation applies to a photon with $\nu \sim m_e c^2$ in the star’s frame, a representative value for a black body spectrum characteristic of the giant outburst of SGR 1806-20, for which $E_p \sim \gamma m_e c^2$. The energy loss length

$$\ell \sim \frac{(m_e c^2)^3}{\epsilon \mathcal{E} \ln \gamma} \sim 10^{-7} \left(\frac{10^{45} \text{ erg/cm}^3}{\mathcal{E}}\right) \text{ cm.}$$

A SGR emitting $P \sim 10^{48}$ erg/s (Hurley et al. 2005; Palmer et al. 2005) from the A ∼ $10^{13}$ cm$^2$ surface area of a neutron star has $\mathcal{E} = 4P/(4\pi) \sim 10^{25}$ erg/cm$^3$; energy loss is extremely rapid.

In order to make up this energy loss by acceleration would require an electric field

$$E_{el} \sim \frac{\gamma m_e c^2}{\ell} \sim 10^{12} \text{ esu/cm.}$$

$^1$ An alternative hypothesis, in which FRB are analogous to Type II Solar radio bursts, suffers from the problem that these are produced in plasma whose density is at least 1/4 of the critical density at the frequency of emission. As a result the dispersion index will not be close to 2, in conflict with observation, unless the emission region has a very small scale height and its contribution to the dispersion is negligible.
Such a field cannot be realized. In vacuum it would rapidly lead to breakdown into a pair gap, as in standard pulsar theory. In the dense equilibrium pair plasma \( E \sim 10^{15} \text{erg/cm}^3 \), \( n_\pm \sim 10^{33} \text{cm}^{-3} \) at temperature \( k_B T \sim m_e c^2 \) required for the emission of \( \sim 10^{45} \text{erg} / (\text{cm}^3 \text{s}) \) observed in SGR 1806-20 it would imply the impossible power density \( E_{\text{rad}} n_\pm c \sim 10^{43} \text{erg} / (\text{cm}^3 \text{s}) \).

### 3.2 Observational difficulties

Men et al. (2019) set upper bounds on the rate of FRB at the locations of six gamma-ray bursts suggested to house “magnetar” neutron stars. The failure of Tendulkar, Kaspi & Patel (2016) to detect a FRB during a fortuitous observation of the great outburst of SGR 1806-20 is a strong argument against the association of FRB with SGR, although collimation of the FRB is a possible loophole. The recent results of Casentini et al. (2019) make the converse argument against the association of FRB with SGR: The AGILE X-ray and gamma-ray satellite viewed two repeating FRB during their outbursts, and no X- or gamma-rays were observed, with upper limits \( \sim 2 \times 10^{46} \text{ergs at the distance of 149 Mpc of FRB 180916} \) (Marcote et al. 2020). This is inconsistent with an outburst like the great outburst of SGR 1806-20. Casentini et al. (2019)’s Source 2 at \( \sim 300 \text{Mpc} \) (an upper bound on its distance implied by its dispersion measure, assuming only standard cosmology) is also likely inconsistent with an event like SGR 1806-20. This argument cannot be evaded by collimation because the thermal soft gamma-ray emission of SGR cannot be strongly collimated. On the other hand, these observational bounds on the ratios of MeV to radio fluxes are consistent with those predicted (Beloborodov 2019; Metzger, Margalit & Sironi 2019) in some magnetar/neutron star models of FRB.

One such giant SGR outburst has been observed in the \( \approx 50 \text{years since the launch of the Vela satellites, corresponding to a rate of} \sim 0.02/\text{year in the Galaxy. The FRB rate per galaxy is much less than this. Although we do not know the luminosity function of SGR giant outbursts, there may be rare outbursts significantly stronger than even the once per \sim 50 \text{years great outburst of SGR 1806-20. If FRB are associated with SGR, the strongest and most observable FRB would plausibly be associated with the most luminous SGR. Association of the repeating FRB observed by Casentini et al. (2019) with such a super-SGR 1806-20 outburst is empirically excluded.}

### 4 FRB SKY DISTRIBUTION

The distribution of FRB on the sky shows no evidence of a Galactic contribution. In contrast, the sky distribution of integrated fluence of every other extra-Solar System astronomical observation of stellar origin, with the sole exception of gamma-ray bursts (GRB), is dominated by the Galactic disc. If observations could be extended for the Galactic GRB recurrence time, it is expected that the Galactic disc would also dominate the GRB fluence. This is a consequence of the dominance of the baryonic mass distribution of the Universe, weighted by the inverse square of distance, by the Galactic disc. It would apply to FRB if they are produced by sources related to stars, provided that even one were present in the Galaxy.

A FRB (or any event) at a Galactic distance of 10 kpc would be about 117 dB brighter than at cosmological \( z = 1; \) luminosity distance of about 7 Gpc) distances. The far (\sim 60°) side-lobe sensitivity of radio telescopes is typically about 60 dB less than their mean beam sensitivity, leaving about 57 dB of headroom for detection of Galactic micro-FRB. They would be detected, with comparable signal-processing systems, in any pulse-sensitive observation if their intrinsic strength (some appropriate combination of radiated power and spectral energy density) were within five orders of magnitude of those of the observed cosmological FRB. Most non-catastrophic transient phenomena (those that do not destroy their sources) in Nature, such as Solar and stellar flares, earthquakes, lightning, SGR outbursts and giant pulsar pulses, have a wide range of strengths, as do FRB (Kumar et al. 2019), with weak events far more numerous than strong ones.

If the differential size distribution of FRB is a power law \( dN / dE \propto E^{-\alpha} \) then the rate of FRB detectable at \( \sim 10 \text{ kpc} \) would be \( \sim 10^{11.7(\alpha-1)} \) times the Galactic rate of FRB strong enough to be detectable from \( z = 1, \) or \( \sim 10^{11.7-14.5} \text{/y}. \) The exponent \( \alpha \) describes the distribution of strengths of all FRB, including those from sources that are too weak to be detectable at cosmological distances as well as weak FRB from sources (like FRB 121102) whose stronger bursts are detectable at those distances. Therefore, \( \alpha \) is likely to be greater than the exponent fitted to the distribution of bursts from an individual source, such as FRB 121102 (Gourdji et al. 2019; Wang & Zhang 2019).

The absence of detected Galactic micro-FRB implies that the Galaxy contains no objects that could emit repeating FRB. It argues against neutron stars as sources because there are many, with ranges of several orders of magnitude of magnetic fields, rotation rates and ages, in the Galaxy; if neutron stars with optimal values of parameters make FRB that can be detected at \( z \sim 1 \), neutron stars with less optimal values of parameters should emit micro-FRB detectable at \( \sim 10 \text{kpc}. \)

This argument does not apply to catastrophic models of FRB (just as it does not apply to supernovae or GRB, that are catastrophic) because in such models there are no micro-FRB (just as there are no micro-SN or micro-GRB). The FRB rate, like the GRB rate, would be so low that none would likely have occurred during the period of observations. Could we integrate long enough, the FRB fluence, like the GRB fluence, would be dominated by the Galactic disc. But we know that repeating FRB cannot be catastrophic.

The choice of a nominal Galactic distance of 10 kpc assumes that the Galactic FRB rate is not dominated by even closer and weaker but more frequent or abundant sources. This holds for the Galactic disc (independently excluded by the isotropic distribution of FRB) if \( \alpha < 3/2 \) and for the isotropic immediate (\( \lesssim 100 \text{ pc} \)) Solar neighborhood if \( \alpha < 2 \). If these conditions are not met, FRB sources must be rare enough that there are none within those distances, which has the same effect as requiring a low \( E \) cutoff on \( dN / dE \). This is a weaker version of the inference that there are no FRB sources within the Galaxy; they are discrete, their number density is finite and their spatial density is cut off at the statistically expected mean distance of the nearest one.
5 FRB 180916.J0158+65

The recently discovered (CHIME/FRB 2020) \( P = 16.35 \) day modulation period of FRB 180916.J0158+65 is much too long to be ascribed to the rotation of a neutron star, whose known rotation periods are \( \sim 10^{-3} - 10^{-4} \) s. It might be a binary orbital or superorbital (disc precession or apsidal advance) period, 10–50 times longer than the orbital period, in analogy to Her X-1, Cyg X-1 and SS433; it neither requires nor excludes a neutron star. The apparent absence of an analogous long period in FRB 121102 may perhaps be attributed to its comparatively few and scattered (though longer) observations, in contrast to the approximately 300 observations of FRB 180916.J0158+65 well distributed over a year (CHIME/FRB 2020).

If this period is orbital (Ioka & Zhang 2020; Lyutikov, Barkov & Giannios 2020), the orbit is circular, the total mass of the binary is \( M \) and the variation of DM around the orbit is \( < \Delta \text{DM} \) then the characteristic value of the electron density in the orbit is bounded:

\[
n_e < \Delta \text{DM} \left( \frac{4 \pi^2}{GM^2} \right)^{1/3} \lesssim 1.5 \times 10^5 \text{ cm}^{-3} \Delta \text{DM} \frac{0.1 \text{ pc/cm}^3}{(M / M_\odot)^{-1/3}}.
\]

A corresponding bound on a mass flow rate may be estimated

\[
M \sim n_e m_p R^2 v \lesssim 10^{13} \frac{\Delta \text{DM}}{0.1 \text{ pc/cm}^3} \left( \frac{M}{M_\odot} \right)^{2/3} \text{ g/s,} \tag{7}
\]

where \( R \) is the orbital radius and \( v \) a flow speed; this, of course, assumes a roughly isotropic wind and does not constrain denser flows that do not intersect our line of sight. This may be related to the absorption of burst radiation, but our ignorance of the plasma temperature and \( M \), that may be \( > M_\odot \), precludes quantification.

The confinement of bursts within about 0.3 of the period, as opposed to a smoother modulation of their rate, suggests intermittent activity in a precessing beam produced by black hole accretion (Katz 2017b), in analogy to the precession of jets in AGN (Lu 1990; Caproni, Mosquera Cuesta & Abraham 2004) and SS433 (Margon 1982). Their possible relation to FRB is supported by the inference of offset massive black holes in dwarf galaxies (Reines et al. 2020) and the identification of FRB 121102 with a dwarf galaxy (Tendulkar et al. 2017) and the offset of FRB 180924 (Bannister et al. 2019) and FRB 190523 (Ravi et al. 2019) from the centers of their host galaxies.

6 DISCUSSION

Neutron star models of repeating FRB are specious. Pulsar-like models imply periodicity that is not observed. They make energetic demands that are difficult to meet. SGR-like models imply periodic modulation that has not been seen. More importantly, no FRB was observed in association with a Galactic SGR and SGR are excluded from association with two extragalactic FRB. Repeating FRB require a different explanation.

If apparently non-repeating FRB are actually one-off, catastrophic events these arguments would not apply to them. There would need to be two different FRB mechanisms, one for repeaters and one for non-repeaters; the latter could involve the birth or death of a neutron star.

The rarity of FRB sources implied by the absence of Galactic micro-FRB excludes stellar mass black holes as well as neutron stars (unless they are so narrowly collimated that none in our Galaxy are observable). A neutron star model might satisfy the constraint of rarity (but not that of aperiodicity) by limiting emission to the very youngest and perhaps fastest rotating or most strongly magnetized stars. No such loophole exists for black holes, whose properties (aside from mass and angular momentum if they are rapidly accreting) do not change with age. The only known objects rare enough to meet the criterion of rarity are intermediate-mass or massive black holes (Katz 2019).

Comparison to FRB 121102 argues against attributing the absence of Galactic neutron star FRB to short active lifetimes. FRB 121102 has been active for seven years, with no apparent sign of decay; a neutron star’s activity, even if decaying, would remain observable at Galactic distances very much longer than at the distance of FRB 121102 at which it would be \( \sim 10^{10} \) times fainter. There are likely between 30 and 300 Galactic neutron stars, with a wide range of parameters (magnetic field, binary companions, spin, etc.), younger than \( 10^4 \) years; any as energetic as FRB 121102 would be brighter than it unless its radiated flux decayed faster than the \( -10/\log_{10}(10^4 \, y/T_{\text{age}}) < -3 \) power of time, where \( T_{\text{age}} \) is the present age of FRB 121102. If FRB sources are neutron stars, they must in some way be distinguished from the overwhelming majority of neutron stars, such as by orientation if FRB emission is narrowly and stably beamed.

Precession of a beam and the disc that feeds and guides it can be driven by the Lense-Thirring effect or nonrelativistically by a massive surrounding disc. In contrast to models (Levin, Beloborodov & Bransgrove 2020; Zanazzi & Lai 2020) based on free precession of a neutron star that predict a smoothly lengthening precession period as the star spins down, and binary models (Ioka & Zhang 2020; Lyutikov, Barkov & Giannios 2020; Yang & Zou 2020) in which orbital and precession periods are stable, models based on a precessing jet produced by black hole accretion are consistent with any trend unless the driving disc is dissipating. A disc remnant of a disrupted star (Nixon & King 2013) would gradually dissipate, the torque it exerts would decline, and the resulting precession period would lengthen.

The observed (CHIME/FRB 2020) maintenance of phase stability in FRB 180916.J0158+65 to \( \Delta \phi \lesssim 1 \) radian over an observation time \( t_{\text{obs}} \) implies a lower bound on a characteristic time scale of steady period change \( t_{\text{char}} \equiv P/|\dot{P}| \gtrsim 2\pi (t_{\text{obs}}/2)^2/(2P^2\Delta \phi) \sim 20 \, y. \)

If FRB are produced in accretion disc funnels or jets, analogous phenomena might be observable in blazars, in which these funnels and jets are directed to the observer, although their dependence on black hole mass, accretion rate and other parameters is unknown.

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