Fast Radio Burst Energetics and Sources

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ABSTRACT
Repeating and apparently non-repeating fast radio bursts (FRB) differ by orders of magnitude in duty factors, energy and rotation measure. Extensive monitoring of apparently non-repeating FRB has failed to find any repetitions. This suggests the two types differ qualitatively, rather than in repetition rate, and are produced by distinct kinds of sources. The absence of periodicity in repeating FRB argues that they are not produced by neutron stars. They may originate in dilute relativistic jets produced by low luminosity black hole accretion. Non-repeating FRB may be produced by catastrophic events such as the collapse of an accreting magnetic neutron star to a black hole or of an accreting magnetic white dwarf to a neutron star, during which a disappearing magnetic moment radiates dipole radiation that accelerates electrons in nearby matter. If they are emitted by collimated beams of relativistic particles or charge “bunches” with Lorentz factor $\gamma$, their radiation is collimated into a solid angle $\sim \gamma^{-2}$ sterad, reducing the energy requirement. If powered by magnetic reconnection, a pulse of length $\Delta t$ may draw on the magnetic energy in a volume $\sim \gamma^4 (c \Delta t)^3$, although only a fraction $\sim 1/\gamma^2$ of this may be dissipated without decollimation.

Key words: radio continuum: transients, magnetic reconnection, stars: pulsars: general, galaxies: quasars: general

1 INTRODUCTION

Fast Radio Bursts (FRB) are rare events. The rate of FRB with fluences at $\sim 1400$ MHz $\gtrsim 1$ Jy-ms (roughly the Parkes detection threshold) is controversial, but estimates are within an order of magnitude of $10^6$/sky-y (Lorimer 2018). Combining with an estimate (Conselice et al. 2016) of $\sim 10^{11}$ $L^*$ galaxies within $z \lesssim 1$ implies a rate of $\sim 10^{-5}$/galaxy-y, three or four orders of magnitude less than the supernova rate (Li et al. 2011). FRB require rare progenitors. If all FRB repeat their sources must be even rarer than the bursts themselves, and if only the fraction known to repeat actually do so, the repeaters must be rarer still.

FRB do not have obvious identifications with other astronomical objects (Tendulkar et al. (2017) identified FRB 121102 with an unremarkable dwarf galaxy). Their sources must be rare and special; if they were abundant, scaling with the density of stars, the luminosity of an active galactic nucleus (AGN), or some other observationally obvious parameter, those at comparatively low redshift would be expected (even with poor localization) to be identified with rich clusters of galaxies, luminous AGN, or other prominent hosts. This gives the modeler great freedom to consider exotic circumstances but makes it difficult to exclude hypotheses on the basis of the special conditions required.

If FRB radiate isotropically, the cosmological distances implied by attributing their dispersion measures to intergalactic plasma in standard cosmology imply instantaneous isotropic equivalent luminosities as high as $\sim 10^{53}$ ergs/s and energies $\sim 10^{50}$ ergs (Thornton et al. 2013). The identification of the first repeating FRB 121102 (Chatterjee et al. 2017; Marcote et al. 2017; Tendulkar et al. 2017; Bassa et al. 2017) with a dwarf galaxy at redshift $z = 0.193$ and the second at $z \leq 0.1$ (CHIME/FRB 2019a) implies their burst energies are a few orders of magnitude lower.

FRB must be emitted in low density plasma because $\sim 1$ GHz radiation cannot propagate through plasma with $n_e \gtrsim 10^{10}$ cm$^{-3}$. In the plasma that produces most of the dispersion, likely some combination of interstellar media in a host galaxy and our Galaxy and the intergalactic medium, $n_e < 5 \times 10^7$ cm$^{-3}$ because in the relation $\Delta t \propto \nu^\alpha$ the dispersion index $| - \alpha - 2 | \leq 0.003$ (Katz 2016a). Higher $n_e$ is possible in regions that are only small contributors to the dispersion.

Do repeating and non-repeating FRB have the same sources and emission mechanisms, differing only in repetition rate, or are they fundamentally different, as suggested by Caleb, Spitler & Stappers (2018); Palaniswamy, Li & Zhang (2018)? Must a single model be found, that with only quantitative modification can explain both repeating and non-repeating FRB, or could the prime
movers of these classes of events differ qualitatively? Can qualitatively different prime movers produce similar radiation, perhaps by the same physical processes? Analogous questions arose in the study of gamma-ray bursts (GRB), that could not be understood until it was recognized that soft gamma repeaters (SGR) are a different phenomenon (Katz 2002; Kulkarni 2018).

Relaxing the requirement that a single model account both for non-repeating FRB and for a repeating FRB that has been observed over five years frees the modeler from constraints that may be mutually contradictory. There is much more freedom in modeling non-repeating FRB if they can be catastrophic events, destroying the source objects, and in modeling repeating FRB if they are not required to meet the energetic requirements of the non-repeaters.

Several differences between the repeating and non-repeating FRB point to their being distinct phenomena:

(i) The difference between repetition and non-repetition is quantified by the duty factor

\[ D \equiv \frac{\langle S \rangle^2}{\langle S^2 \rangle} \]  

(Katz 2016b), where \( S \) is the flux density. The repeater FRB 121102 had \( D \sim 2 \times 10^{-6} \) during a period of high activity (Zhang et al. 2018), while for non-repeating FRB \( D < 10^{-9} \) may be inferred from their long-term absence of repetitions (Shannon et al. 2018). This difference of at least three orders of magnitude in \( D \) suggests that the sources are qualitatively different.

(ii) The instantaneous isotropic-equivalent power implied by the repeating bursts is about three orders of magnitude less than that required by the non-repeaters because of the repeaters’ lower intensity and smaller distances: \( z = 0.195 \pm 0.01 \) (Venn et al. 2017; CHIME/FRB 2019a) rather than \( z \sim 1 \) for many non-repeaters. In addition, repeaters may be collimated (Katz 2017a), further reducing their required power, while in some models the event rate of the non-repeaters implies that they are not collimated (Sec. 9.1.1).

(iii) The rotation measure (RM) of the repeating FRB 121102 (it has not been reported for the second repeater FRB 180814.J0422+73 CHIME/FRB (2019a)) is \( \gtrsim 10^3 \times \) the measured RM of non-repeating FRB (Gajjar et al. 2018; Michilli et al. 2018). This also suggests a qualitative difference.

(iv) Both repeaters show downward spectral drifts within their pulses (Gajjar et al. 2018; Michilli et al. 2018; Hessels et al. 2019; CHIME/FRB 2019a); this has not been reported in non-repeaters.

(v) Non-repeating FRB have a characteristic energy scale while the bursts of the repeating FRB 121102 appear not to have such a scale.

Sec. 2 discusses the differences in rotation measure. They imply that repeating and non-repeating FRB originate in different environments, and therefore likely are of different nature. Sec. 3 considers the hypothesis of neutron star origin and discusses its weaknesses. Sec. 4 discusses the failure to detect periodicity in the repeating FRB 121102, an argument against neutron star models. Sec. 5 discusses the distribution of non-repeating FRB on the sky. This implies that their sources are rare and that there is a characteristic strength of their outbursts; none occurred in the surveyed region of the Galaxy (no low energy Galactic “nano-FRB” have been detected).

The problem of describing the emitting region and mechanism should be separated from the problem of the prime mover, the ultimate energy source. Non-repeating and repeating FRB may have similar emission processes but different prime movers. Sec. 6 explores the energetics of such a possible physical process: magnetic reconnection of two discrete low density regions of uniform (on the scale on which magnetic reconnection takes place) magnetic induction. Magnetic reconnection can produce collimated radiation if it accelerates relativistic particles. Sec. 7 applies this to FRB and pulsar nanoshots.

Sec. 8 presents a model of repeating FRB resulting from magnetic reconnection in long-lived regions of turbulent gas flow, such as relativistic jets produced by accretion onto black holes (accretion discs themselves are too dense to permit the escape of GHz radiation). Repetition may continue indefinitely. There is no evident characteristic scale of outburst, and the sources, AGN or other accreting massive black holes, are rare. Such a model avoids the energetic problems of neutron star models of the repeating FRB 121102, especially those that describe FRB as scaled-up giant pulsar pulses (Katz 2017a; Wang et al. 2018).

Sec. 9 discusses the origin of non-repetitive FRB in catastrophic events that destroy their sources. Even if not “standard flashbulbs”, their total emitted energy appears to be dominated by the most energetic outbursts. These events may be the collapse of accreting magnetic neutron stars to black holes, or of accreting magnetic white dwarfs to neutron stars.

Conclusions are summarized in Sec. 10.

2 Rotation Measure

Rotation Measure, defined by the integral

\[ \text{RM} \equiv \int n_e B_d \, dl \]  

along the line of sight (and usually parametrized by the rotation angle of linear polarization \( \Delta \theta(\lambda^0/\lambda^2) \)), is dominated by the near-source environment. Although the intergalactic medium may be the dominant contributor to dispersion measure (DM), it contributes negligibly to RM. Both electron density and magnetic field are small in the intergalactic medium, compared to their interstellar or near-source values, and RM is second-order in these small quantities.

Rotation Measures may be significant clues to the origins of FRB. The repeating FRB 121102 has \( \text{RM} \approx 1.4 \times 10^5 \text{ rad/m}^2 \), which varied by about 10% in seven months (Michilli et al. 2018). This is reminiscent of PSR J1745-2900 with \( \text{RM} \approx 7 \times 10^4 \text{ rad/m}^2 \), varying 5% in 1–2 years (Desvignes et al. 2018). PSR J1745-2900 has a projected separation of 0.097 pc from the Galactic Center black hole source Sgr A* (Bower et al. 2015). Sgr A* itself has \( \text{RM} \approx -5 \times 10^7 \text{ rad/m}^2 \) (Bower et al. 2018).

1 These values depend on the sensitivity of the observations and can only be lower limits because any emission below the detection threshold is not included. See Sec. B for discussion.

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Analogies suggest that FRB 121102 is causally associated with or even identical to the persistent radio source in its host galaxy. This persistent source is consistent with being a low luminosity AGN (Marcote et al. 2017). The measured upper limit on their projected separation of 40 pc, \( \sim 1\% \) of the size of the galaxy, is small enough to render an accidental coincidence implausible.

The measured RM of non-repeating FRB are all smaller by at least three orders of magnitude than that of FRB 121102 (the RM of the second repeater FRB 180814.J0422+73 has not been measured CHIME/FRB (2019a)), and are comparable to those of Galactic pulsars (Michilli et al. 2018). The most extreme example is FRB 150215, for which \( -9 < \text{RM} < 12 \, \text{rad/m}^2 \) (Petroff et al. 2017). This indicates that non-repeaters are distinct from repeating FRB, occur in different environments and therefore likely have different sources. Non-repeaters are not associated with galactic nuclei, that have much higher RM (Pasetto et al. 2016).

3 WHY NOT NEUTRON STARS

Many models of FRB (see reviews by Katz (2018a); Platts et al. (2018)) assume their sources are magnetic neutron stars and their origin is either as super-giant pulsar pulses or in SGR outbursts. Magnetic neutron stars are candidates because their small size and high magnetic, gravitational and rotational energy densities appear a natural match to the brevity and high power of FRB. The facts that both radio pulsars and FRB have extraordinary brightness temperatures, implying coherent emission, and that some pulsars emit occasional giant pulses, have made giant pulsar (PSR) pulses writ large a popular model of FRB.

3.1 Pulsar Models

The super-giant pulsar pulse model of FRB has the difficulty that in standard pulsar models the instantaneous radiated power cannot exceed the instantaneous spindown power. The requirement of an instantaneous power as large as \( 10^{38} \, \text{ergs/s} \), without any intermediate energy reservoir between rotational energy and radiation, would demand extreme values of both the pulsar’s magnetic moment and its rotation rate. Appendix A also argues that neutron stars are not born with the required combination of fast (near-breakup) spin and huge (“magnetar”) magnetic moment.

The rotational energy store of a neutron star is limited by its equation of state (and hence its maximum rotation rate), independent of its magnetic moment. In a pulsar model that store must be no less than the peak (burst) radiated power multiplied by the active lifetime of the neutron star as a source of FRB. These values are so extreme as to verge on contradicting the lower bound on \( \Delta \) FRB lifetime set by the observation of FRB 121102 over six years (Katz 2018a). This problem might be avoided if there is an energy store intermediate between rotation and bursts that can be drawn upon for short periods, as a discharging capacitor (Katz 2017b) powers a spark.

Collimation (Katz 2017a) provides another possible loophole by reducing the required power from its isotropic-equivalent value, perhaps by a large factor. The extraordinary brightness temperatures of FRB require radiation by charge “bunches” whose net charges are so large that their electrostatic potentials are \( \gg m_e c^2/e \), implying that they can only hold together if the radiating electrons are highly relativistic (Katz 2014, 2018b). Radiation by relativistic particles is collimated if the particle velocity vectors are themselves collimated. In a pulsar magnetosphere a particle moving along a magnetic field line sweeps its radiation cone over an angle \( \sim 1 \) radian, and the field lines themselves spread over \( 2\pi \) radians in azimuth, arguing against the collimation loophole to the energy requirement.

3.2 Soft Gamma Repeater Models

An alternative model, also based on a magnetic neutron star, associates FRB with Soft Gamma Repeater (SGR) outbursts (Katz 2016b, 2018a). It has several difficulties: 1) No FRB was observed simultaneous with the great outburst of the Galactic SGR 1806–20 (Tendulkar et al. 2016); even far out-of-beam, a Galactic FRB would be about 50 dB more intense than one at cosmological distance. 2) SGR are thermal emitters with a dense photon-pair gas environment that would rapidly degrade energetic particles by Compton, Blahha and Møller scattering and prevent the development of large accelerating electric fields by the enormous conductivity of the pair gas. 3) The activity of FRB 121102 is not modulated at periods characteristic of SGR (Zhang et al. 2018) (or any other period).

4 ABSENCE OF PERIODICITY

Two distinct kinds of periodicity should be distinguished. In \textit{absolute periodicity}, the intervals between pulses are integer multiples of an underlying period, while in \textit{continuous modulation} the rate of bursts or their intensity is periodically (not necessarily sinusoidally) modulated, but individual bursts need not be separated by integer multiples of a period. In the limit as the modulation function approaches a Dirac \( \delta \)-function, continuous modulation becomes absolute periodicity. Slow continuous changes in periods may be readily included in these models.

4.1 Absolute Periodicity

Radio pulsars are absolutely periodic, aside from their gradual slowing and infrequent small discontinuous period changes (glitches). Their pulses are observed at most or all periodically spaced times (some pulses may be absent, or “nulled”). Rotating Radio Transients (RRAT) (McLaughlin et al. 2006) are Galactic pulsars, the overwhelming majority of whose possible pulses are nulled. This could be the result of no pulse being emitted or of emitted pulses that are not directed toward the observer. RRAT are discovered as single pulses spaced by large multiples of the underlying period and whose periodicity may only be revealed by sustained monitoring.

Absolute periodicity is comparatively easy to detect, or to exclude, because even a single out-of-phase burst is sufficient to exclude that combination of period and phase. Approximately \( \log_2 (T_{\text{pan}}/P_{\text{min}})/(-\log_2 D) \) bursts must be observed, where \( D \) is the duty factor (the fraction of the
rotational period during which a burst may be emitted, including any measurement uncertainty) to be confident of detecting, or excluding, a period greater than $P_{\text{min}}$ in a span of data $T_{\text{span}}$. Very close burst pairs, if representing separate bursts rather than substructure of longer bursts, are equivalent to small $T_{\text{span}}$ and are powerful tools for constraining possible absolute periodicity (Katz 2018c).

### 4.2 Continuous Modulation

In an alternative model, the brightness or flux of bursts is modulated continuously, such as by neutron star rotation. Bursts are equally likely to occur at any modulation phase, but will be brighter and more often detected at some phases than at others. Such modulation is likely in neutron star models in which emission is not narrowly collimated, but in which radiation is brighter when the emitting region is on the side of the neutron star facing the observer, and not occulted by the star. This describes the modulation of anomalous X-ray pulsars (AXP/SGR) and of accreting binary neutron stars.

Continuous modulation is inconsistent with narrow collimation in a direction fixed in the frame of the rotating source. A narrowly collimated rotating beam will only be observable at times separated by integer multiples of the rotation period, when it points to the observer; this is absolute periodicity. Continuously modulated models therefore require that FRB be uncollimated and extremely luminous, with actual luminosities comparable to their isotropic-equivalent luminosities.

In continuously modulated models periodicity may be manifested as bursts at favorable phases are more readily detected, or as bursts as those phases are brighter, on average, than those at less favorable phases. This second effect occurs only if there is an intrinsic characteristic scale of burst brightness, fluence, or other detectability parameter independent of modulational phase. It does not occur if the distribution of the detectability parameter is a power law $N(L) \propto L^{-\beta}$, because then $(L)_{L > L_0} = L_0(1 - \beta)/(2 - \beta)$ (the finitude of the total emission requires $\beta > 2$ and a lower cutoff below the range of observation, as described in Sec. 5). Because bursts can occur at any phase of the periodic modulation, an out-of-phase burst does not exclude a period, but only renders it less likely in a Bayesian sense.

Detection or exclusion of periodic modulation is more difficult than detection of absolute periodicity. If the modulation is sinusoidal with fractional amplitude $a$ it requires the detection of roughly $\log_2(T_{\text{span}}/P_{\text{min}})/a$ bursts, typically several dozen.

### 4.3 FRB 121102

Examination of the very short (3–100 ms) burst intervals reported by Scholz et al. (2017); Hardy et al. (2017); Zhang et al. (2018) excludes any absolute periodicity unless these short intervals represent substructure of longer ($\gtrsim 100$ ms) bursts rather than separate bursts. If bursts are that long, the necessarily even longer periods are excluded by timing of the longer intervals. The analysis of Zhang et al. (2018) can also be interpreted as setting an upper bound on the amplitude of any continuously modulated periodicity of $\lesssim 30\%$.

Pulsars are known with much shorter periods than the absolute periods $\gtrsim 10$ ms excluded by Zhang et al. (2018), and energetic considerations require very short periods in pulsar models of FRB (Katz 2018a). However, the failure to detect periodicity encourages consideration of models that have no periodicity of either kind, and therefore that do not involve a rotating neutron star.

### 5 SKY DISTRIBUTION AND RARITY OF FRB

FRB sources are rare in the Universe. This is shown by their dispersion measures, substantially attributed to intergalactic plasma and implying cosmological distances. Statistical arguments are possible only for the non-repeating FRB.

If the sources of non-repeating FRB were distributed similarly to stars, as expected in any model that associates them with objects related to stars, the distribution of their flux on the sky would resemble that of starlight. It does not. Non-repeating FRB are not concentrated in the Galactic plane (Bhandari et al. 2018). Yet most of the starlight in the sky is Galactic, and concentrated in the plane: At $\lambda = 2-2.5 \mu$ (K-band) where extinction is comparatively small, the extra-Galactic background light is $\sim 10 \text{nW m}^{-2} \text{sr}^{-1}$ (Domínguez et al. 2011) while the Galactic starlight is $\sim 300 \text{nW m}^{-2} \text{sr}^{-1}$ at $b = 30^\circ$ and even more in the Galactic plane (Leinert et al. 1998). Allowing for extinction further increases the ratio of plane to high latitude starlight and the difference between the distributions of starlight and of non-repeating FRB. Either:

(i) The density of non-repeating FRB sources does not follow that of stars, or

(ii) Non-repeating FRB sources are so rare that no Galactic outbursts have been observed.

The first explanation would indicate that non-repeating FRB are not emitted by objects associated with stars or their descendants, such as neutron stars (X-ray binaries and pulsars). Such a model is considered for repeating FRB in Sec. 8.

The second explanation would require that non-repeating FRB sources, including hypothetical sources of more frequent but extremely low energy nano-FRB in the Galaxy, are also too rare to have been detected. It argues against pulsar models (Sec. 3) that would be expected to have many small outbursts for each FRB super-outburst. Averaging over sufficient time and solid angle would lead to a flux distribution on the sky resembling that of stars, although the required average might be over thousands or millions of sterad-years.

The second explanation is consistent with non-repeating FRB sources that are very rare neutron star events or subspecies, none of which are now active in the Galaxy. These might be neutron stars less than a few decades old, or with unprecedented magnetic fields, or undergoing very rare, perhaps catastrophic, events such as the collapse discussed in Sec. 9.1. It would require the existence of a large characteristic energy scale, so that the non-repeating FRB flux during the period and in the directions of observation when no characteristic bursts are observed is much less than its mean, averaged over sufficient time and solid angle. SN, GRB and SGR have such characteristic scales,
but known stellar flares and giant pulsar pulses do not; their flux is dominated by the weakest events (Cordes et al. 2004; Popov & Stappers 2007; Kazantsev & Potapov 2017; McKee et al. 2018). The distribution of bursts from the repeating FRB 121102 is not well determined, but within the dynamic range of observation their flux is dominated by weak bursts (Law et al. 2017; Zhang et al. 2018; Gourdji et al. 2019); they do not have a characteristic scale in the sense used here.

There are no Galactic FRB among the 65 observed FRB (Petrolf et al. 2016). With about 95% confidence, the Galactic fraction $f_G \lesssim 0.06$. The ratio of weak non-repeating bursts detectable at Galactic distances (only from one galaxy, ours) to those detectable from the $N_g \sim 10^{11}$ galaxies in the Universe with $z \lesssim 1$ must be $< f_G N_g \approx 6 \times 10^9$. Galactic nano-FRB would be detectable with emission $E_G \approx (10 \text{kpc}/3 \text{Gpc})^2 \sim 10^{-11}$ of those of cosmological FRB. If the distribution of emission strengths is a power law $n(L) \propto L^{-\beta}$, the exponent $\beta = -\ln f_G N_g / \ln E_G - 1 \approx -0.1$. Any energy emitted by Galactic nano-FRB with the same $S/N$ as the observed cosmological FRB is much less than that emitted by the cosmological FRB. This does not contradict the expectation that, averaged over a sufficiently long time, if FRB are produced by a stellar-related population, the FRB fluence received from the very infrequent Galactic FRB will far exceed that of extra-Galactic FRB because of the proximity of Galactic objects.

If FRB have a characteristic energy scale, with their total mean flux dominated by infrequent large outbursts, then the rarity of FRB implies the rarity of outbursts but not the rarity of their sources, whose outbursts could be very infrequent or occur only once. For example, the Galaxy could contain many proto-FRB that will produce a burst once in the distant future.

The slope of the distribution of FRB fluences may be too uncertain (Macquart & Ekers 2018a,b; James et al. 2019) to address this question, but the fact that the high-fluence ASKAP FRB (Shannon et al. 2018) have a mean DM (and hence distance) about half that of the Parkes FRB (Li, Yalinewich & Breyse 2019) weakly constrains the distribution of fluences—detections by the more sensitive Parkes telescope are not dominated by less luminous bursts from nearby sources (Sec. 9). This is consistent with the inference from the distribution of FRB on the sky. The slopes of the distributions $N(DM)$ and $N(Fluence)$ of the ASKAP FRB Lu & Piro (2019) are similar to those of the Parkes FRB Katz (2016a).

## 6 MAGNETIC RECONNECTION

Magnetic reconnection, the rapid dissipation of magnetostatic energy in a thin current sheet, is an incompletely understood phenomenon that is known to accelerate charged particles in plasmas ranging from the laboratory to the Sun, the solar wind and its interaction with planetary magnetospheres and is hypothesized to explain many other cosmic phenomena (Lewis, Antiochos & Drake 2011; Gonzalez & Parker 2016). Like other collective fluid structures, it can occur when microscopic dissipative processes are slow (Reynolds or magnetic Reynolds numbers are large). It has recently been proposed to explain some forms of the coherent radio emission of pulsars (Philippov et al. 2019). Here I suggest it as a possible mechanism for the acceleration necessary to make coherently radiating relativistic charge “bunches” that emit FRB.

Two regions of differing magnetic induction are separated by a thin current sheet. In a force-free configuration $(\vec{E} \times \vec{B} = 0)$ the electrons move along the magnetic field lines. If the magnetic induction is nearly unidirectional through the reconnection region, the total radiation has the relativistic collimation of the radiation by individual particles (or charge “bunches”). However, a current $\vec{J} \parallel \vec{B}$ leads to a rotation by an angle $\Delta \theta$ of the direction of $\vec{B}$ through the current sheet while its magnitude does not change. To maintain the collimation of relativistic motion with Lorentz factor $\gamma$ requires $\Delta \theta \lesssim 1/\gamma$, and $|\Delta B| \lesssim \Delta \theta B \sim \langle |\vec{B}|/\gamma \rangle$.

As a result, only a small fraction of the magnetostatic energy can be transformed to kinetic energy of collimated relativistic charged particles. The mean energy density that can be released by magnetic reconnection between equal volumes with inductions $B_2$ and $B(\hat{x} \cos \theta + \hat{y} \sin \theta)$ for $\theta \sim 1/\gamma \ll 1$ is

$$\mathcal{E} \approx \frac{B^2}{32 \pi} \theta^2 \sim \frac{B^2}{32 \pi \gamma^2}.$$ (3)

The inefficiency of tapping the magnetostatic energy is compensated by the fact that the emission is narrowly collimated; the radiated power required to provide the fluence illuminating an observer fortunate enough to be within an angle $\lesssim 1/\gamma$ of the beam is $\propto \gamma^{-2}$. Of course, to maintain the observed FRB rate and total energy radiated as FRB, if they are collimated there must be a greater rate of FRB-radiating events, but as we have no information about this rate (as opposed to the rate of those directed toward us, that we detect), there is no inconsistency.

If magnetic reconnection is the source of FRB emission, we can set lower bounds on the magnitudes of the fields. Particles distributed over a length $\Delta t$ in the local rest frame moving towards the observer with a speed $v$ produce a pulse of duration

$$\Delta t \sim \frac{\Delta t}{v - c} \sim \frac{\Delta t}{2c\gamma^2}.$$ (4)

This result yields only an upper bound on $\Delta t$ because $\Delta t$ may be increased by causes other than propagation delays over the path to the observer in the emitting region. For example, particle acceleration may be continuous, or repeated, in a smaller radiating region.

We do not know the thickness of the region whose magnetostatic energy contributes to the radiation received in the time $\Delta t$, but if reconnection is rapid it may be $\sim c \Delta t$. Because the source is very distant from the observer the dimension in the third direction of the radiating region is not limited by causality. The third dimension of the reconnecting patch is unknown, but is plausibly comparable to its line-of-sight dimension $\Delta t$. Then the radiation can draw on the magnetostatic energy in a volume

$$V \lesssim 4\gamma^4 (c \Delta t)^3.$$ (5)

Because $\Delta t$ is an upper limit this is (aside from the assumed size in the third dimension) an upper limit on $V$.

The energy radiated over a time $\Delta t$ into a solid angle $\sim 1/\gamma^2$ to produce an observed flux density $S$ over the
bandwidth $\Delta \nu$ is

$$E = \frac{S \Delta \nu \Delta t d^2}{\gamma^2},$$

where $d$ is the distance to the FRB. Equate this energy to that available by magnetic reconnection in the source region

$$E = EV.$$  

Equations 3, 5, 6, and 7 yield

$$B \gtrsim \sqrt{\frac{8\pi S \Delta \nu d^2}{\gamma^2 c^2 (\Delta t)^2}}.$$  

Because Eq. 5 is only an upper limit this result is a lower limit on $B$ as a function of $\gamma$. Higher $\gamma$ relax the constraints on $B$.

This constraint applies to fields produced by currents in the magnetized region. Magnetostatic energy attributable to currents elsewhere (for example, in a pulsar magnetosphere whose fields are largely attributable to currents within the neutron star) cannot be dissipated by reconnection.

In order to produce collimated radiation efficiently, the beam of “bunches” of charge $Q$ must lose much of its energy before it is significantly deflected by the acceleration that makes it radiate. The radiation time

$$t_{rad} \lesssim \frac{\rho}{\gamma c},$$

where $\rho$ is the radius of curvature of the bunches’ path. Comparing the energy lost in $t_{rad}$ to the kinetic energy of the electrons,

$$2 \frac{4Q^2 e}{\rho c^2} t_{rad} \lesssim \frac{Q}{e} mc^2,$$

or

$$\gamma^2 \frac{Q}{\rho} \gtrsim \frac{mc^2}{e}.$$  

Hence if the radiation is to be collimated to the maximum degree permitted by the Lorentz factor, that Lorentz factor must satisfy

$$\gamma \gtrsim 4 \times 10^4 \left( \frac{Q}{1 \text{Coulomb}} \right)^{-1/2} \rho_6^{1/2}.$$  

FRB brightnesses require $Q \gg 1$ Coulomb (Katz 2018b) so this condition, although demanding, may not be impossible. This degree of collimation is not required by observation, so that Eq. 12 only defines a characteristic $\gamma$. Less collimated radiation is possible, but would require greater total power, a difficulty for energy-limited pulsar models.

The observation of circular polarization in one FRB (Petroff et al. 2015) (there are additional arguments in favor of radiation by collimated beams of charges. Radiation by relativistic charges moving in a plane (defined by their instantaneous velocity and acceleration vectors) is linearly polarized in directions in the plane of motion, but partly circularly polarized in opposite senses on opposite sides of that plane (Kumar, Lu & Bhattacharya 2017). If the radiation pattern is broadened to an angle $\gg 1/\gamma$ then the ray to the observer will be on opposite sides of (“above” and “below”) planes of motion of different radiating charges and the circular polarization will average to a small value. Only if the radiating particles are collimated to an angle $\lesssim 1/\gamma$ will the ray to an observer (within an angle $\sim 1/\gamma$ but not $\ll 1/\gamma$ of the mean plane of motion) be on the same side of most or all of the particles’ planes of motion, and a substantial net circular polarization be observed. However, Sec. 9.1.1 argues that non-repeating FRB are not collimated.

7 ENERGETICS

7.1 Poynting flux

Jets from accretion onto massive black holes may be powered by Poynting flux whose source is in the inner accretion disc. Poynting flux may be deposited in the boundary between a jet and a much denser accretion disc or funnel, accelerating particles that may radiate along the jet. The power per unit area $B_P c \cos \theta/8\pi$, where $\theta$ is the angle of incidence, may exceed that of reconnection of a quasi-static field $\sim B_P^2 c / 8\pi$ because the entire Poynting flux incident on denser plasma may be converted to collimated radiation (rather than only the fraction $1/\gamma^2$) if collimation is maintained by a quasi-static field. In addition, Poynting flux propagates at the speed $c$, while the speed of magnetic reconnection may be much less than $c$.

7.2 FRB

Curvature radiation at frequency $\nu$ by electrons accelerated by magnetic reconnection implies $\gamma \gtrsim \gamma_{\text{min}} \equiv (\rho \nu / c)^{1/3}$ and (Eq. 8)

$$B \gtrsim \sqrt{\frac{8\pi S \Delta \nu d^2}{c^2 (\Delta t)^2} \left( \frac{\rho \nu}{c} \right)^{-2/3}}.$$  

if $\gamma \sim \gamma_{\text{min}}$. For representative FRB parameters ($S = 1 \text{ Jy} = 10^{-23} \text{ erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}$, $d = 3 \text{ Gpc} \approx 10^{28} \text{ cm}$, $\Delta t = 10^{-3}$ s, $\nu = 10^{10} \text{ Hz}$ and $\Delta \nu = 10^9 \text{ Hz}$)

$$B \gtrsim \frac{9 \times 10^4}{\rho_6} \times \gamma_{\text{min}}^{-2/3}.$$  

where $\rho_6 = \rho / 10^6 \text{ cm}$. Because of the weak ($\nu^{1/3}$) dependence of the radiated power at frequencies below the spectral peak, significant radiation may be produced by electrons with $\gamma \gtrsim \gamma_{\text{min}}$. Lower values of $B$ are possible. The spectrum could also extend to frequencies much greater than the $\sim 10^9 \text{ Hz}$ assumed in the preceding paragraph.

7.3 Pulsar nanoshots

Pulsar nanoshots (Soglasnov et al. 2004; Hankins & Eilek 2007) have long presented the paradox that these extremely brief (nanosecond) bursts of coherent radiation (that might be considered a model of FRB, despite durations six orders of magnitude shorter and isotropic-equivalent powers six orders of magnitude less) appear to emit more energy than the magnetostatic energy stored in a volume $\sim (c \Delta t)^3$. Allowing for the relativistic effects of Sec. 6 resolves the paradox as collimation would reduce the required energy and magnetostatic energy could be drawn from a larger volume.

Using plausible parameters for PSR B1937+21 (Soglasnov et al. 2004) yields (Eq. 8) $B \gtrsim 5 \times 10^7 \gamma^2$ gauss, and for the Crab pulsar (Hankins & Eilek 2007) $B \gtrsim 1.5 \times 10^9 \gamma^2$ gauss. For $\gamma > 30$ (roughly the value required for
curvature radiation near the surface to radiate at $\sim 1$ GHz; near the light cylinder radius of the Crab pulsar it would imply larger $\gamma$) these values are smaller than the dipole fields at the light cylinder radii, which are $\sim 10^6$ gauss for each pulsar (McKee et al. 2018). The reconnection hypothesis does not require, on energetic grounds, larger magnetic fields than are present.

Soglasnov et al. (2004) used Eq. 5, omitting the factor of $\gamma^2$ and assuming isotropic radiation, thus neglecting another possible factor of $\gamma^2$, to compare the energy emitted in a nanoshot of PSR B1937+21 to the pulsar’s magnetostatic energy density, and found the disturbing result that the emitted energy exceeded the magnetostatic energy of the source region. Allowing for the factors of $\gamma$ resolves this paradox.

8 REPEATING FRB

8.1 Accreting Black Hole Jets?

Massive black holes and their accretion discs and jets (Romero et al. 2016; Vieyro et al. 2017; Katz 2017c; Zhang 2017) may be the sites of repeating FRB. Their emission would not be periodic. They would have indefinite lifetimes, unlike pulsar-like sources whose lifetimes would be limited by spindown and, if long, by magnetic field decay. Like the accretion discs and jets observed in X-ray binaries and AGN, they would fluctuate, with temporal structure on a broad range of time scales. All these properties are consistent with observations of the repeating FRB 121102 (Zhang et al. 2018).

The repeating FRB 121102 has periods of greater and lesser activity (Spitler et al. 2016; Scholz et al. 2016, 2017; Hardy et al. 2017; Law et al. 2017; Gajjar et al. 2018; Houben et al. 2019). The statistics of the intervals between the repetitions during one five-hour observing session with a low detection threshold and during which it was particularly active (Zhang et al. 2018) are shown in Fig. 1.

The identification of FRB 121102 with a star forming region of a dwarf galaxy (Marcote et al. 2017) that also contains a persistent radio source consistent with a weak accreting massive black hole (Chatterjee et al. 2017) supports this association: the FRB may be produced in the environment of a black hole, perhaps by magnetic reconnection in a relativistic jet or by deposition of Poynting flux. The plasma frequency of such a jet, unlike that in an accretion disc, can be low enough to permit the radiation to escape.

The projected separation of $< 40$ pc between FRB 121102 and the persistent source would be very unlikely ($p \lesssim 10^{-3}$) if the FRB source were drawn from a population with the same distribution as the galaxy’s visible light, spread over several kpc, implying association with the persistent source itself. As discussed in Sec. 2, the high and varying rotation measure of FRB 121102 is also consistent with what we know of the environment of the Galactic Center black hole Sgr A*, plausibly an analogue of the (hypothetical) black hole powering the persistent source near FRB 121102: The Galactic Center pulsar PSR J1745–2900 has a rotation measure similar, and similarly varying, to that of FRB 121102, suggesting that this may be a general characteristic of the regions around massive black holes.

8.2 Rarity

Bhandari et al. (2019) have shown that the space density of repeating FRB with characteristics similar to those of FRB121102 is $< 10^{-5}$ Mpc$^{-3}$. This should be compared to the density of galaxies, $\sim 0.003$ Mpc$^{-3}$ for L$^*$ galaxies and $\sim 0.1$ Mpc$^{-3}$ for all galaxies (Conselice et al. 2016). It implies that the sources of repeating FRB are extraordinarily rare in the Universe, rarer even than the massive black holes of galactic nuclei. If repeating FRB are associated with these black holes another restrictive condition must also be satisfied. A plausible candidate is collimation consistent with the discussion of particle acceleration in magnetic reconnection in Sec. 6)—FRB are only observed if the radiation and the accelerating electric field is pointing towards the Earth (Katz 2017a).

8.3 Propagation of radiation in a jet

At a distance $r$ from the source of a jet with power $L_{jet}$ in
particle kinetic energy, the lepton density

\[ n_e = \frac{L_{\text{jet}}}{\Omega r^2 \nu_{\text{jet}}^3}, \]  

(15)

where \( \Omega \) is the jet’s solid angle, \( \mu \) is the mass per lepton (for a purely leptonic jet \( \mu = m_e \) but for a baryonic jet \( \mu \approx m_p \)) and \( \gamma_{\text{jet}} \) is the Lorentz factor of the lepton, including both bulk jet motion and their disordered motion within the jet. For \( L_{\text{jet}} \approx 10^{40} \text{ergs/s} \), \( \Omega \approx 0.01 \) and \( r = 10r_{\text{Sch}} \), where \( r_{\text{Sch}} \) is the Schwarzschild radius and \( M = 10^5 M_\odot \), \( n_e = 2 \times 10^7 \gamma_{\text{jet}}^{-3} \text{cm}^{-3} \) for a baryonic jet and \( n_e = 5 \times 10^8 \text{cm}^{-3} \) for a leptonic jet. \( L_{\text{jet}} \) may be only a small fraction of the accretion luminosity if much of the power is carried by Poynting flux rather than by particle kinetic energy.

The plasma frequency in its frame of a jet of relativistic leptons is

\[ \nu_p = \sqrt{\frac{n_e c^2}{\pi m_e \gamma_e}}, \]  

(16)

where \( \gamma_e < \gamma_{\text{jet}} \) is a mean lepton Lorentz factor in the frame of the jet. The values of the parameters are very uncertain but \( \gamma_e \gg 1 \) is likely. The frequency in the observer’s frame is blue-shifted from that in the jet frame (more than outweighing the transformation of \( n_e \), which enters to the 1/2 power), the observed ~ 1 GHz radiation may propagate through such a jet. This also explains the failure to detect FRB 121102 at 150 MHz (Houben et al. 2019) without attributing it to scattering.

The dependence of \( n_e \) (Eq. 15) and hence of \( \nu_p \) (Eq. 16) on \( L_{\text{jet}} \) may explain the low luminosity of the persistent source associated with the repeating FRB 121102: FRB produced in denser and more energetic jets cannot emerge to be observed.

9 NON-REPEATING FRB

The failure to observe any repetition of apparently non-repeating FRB during 4.5 \times 10^7 s of cumulative observation (Shannon et al. 2018); if all are drawn from the same ensemble this is equivalent to the same total duration of observation of a single FRB) suggests that they truly do not repeat, emitting only one burst in their lifetimes. Their observation of a single FRB) suggests that they truly do not repeat, emitting only one burst in their lifetimes. Their

\[ \langle d \rangle = \frac{d_{\text{max}}}{5 - 2\beta}, \]  

(17)

where we have assumed \( \beta < 5/2 \). If this condition is not met the normalizing denominator diverges unless a near-observer cutoff is introduced, and if \( \beta \geq 3 \) the numerator also requires such a cutoff. If \( \beta \leq 1 \) the \( L \) integrals diverge, so this result is valid only in the plausible range \( 1 < \beta < 5/2 \); Lu & Piro (2019) suggest \( \beta \approx 1.7 \) (if \( \beta < 2 \) the total FRB energy or luminosity diverge at the high energy limit of the integral over \( L \) and another cutoff must be introduced in evaluating it). This result differs from that of Li, Yalinewich & Breysse (2019) because of the introduction of a cosmological cutoff, violating their Euclidean assumption. Eq. 17 expresses the near-independence of the mean DM on the sensitivity of the survey, which now supports the attribution of most of the dispersion to the intergalactic medium and cosmological distances of FRB. If, as must be the case, the cosmological cutoff is not abrupt, \( \langle d \rangle \) will have some dependence on \( F_0 \), as observed (Shannon et al. 2018; Li, Yalinewich & Breysse 2019).

If, instead, there is a characteristic strength \( L_0 \) with \( n(L) \propto \delta(L - L_0) \) and \( L_0 > 4\pi d_{\text{max}}^2 F_0 \), then \( \langle d \rangle = 3d_{\text{max}}/4. \) The empirical near-independence of \( DM \) (approximately proportional to \( d \) for \( z \lesssim 1 \)) of \( F_0 \) is consistent with either a power law distribution of \( L \) or a distribution peaked at a strength sufficient for observation out to \( z \sim 1 \).
The fact that the ASKAP detection rate of $1.4 \times 10^4$/sky-yr (Shannon et al. 2018) is nearly two orders of magnitude less than the rate in the same frequency band of the more sensitive Parkes survey of $\sim 10^5$/sky-yr (Lorimer 2018) points toward the power law, or some other broad, distribution. However, rejection of the $\delta$-function distribution does not contradict the inference (Sec. 5) of a characteristic scale of strength of non-repeating FRB.

9.1 Collapsing Neutron Stars

Non-repeating FRB may involve the destruction of their progenitors. Falcke & Rezzolla (2014) suggested that FRB are produced by the collapse of rotationally stabilized neutron stars with masses greater than the maximum mass of a non-rotating neutron star after they lose their angular momentum. Yet there is no compelling evidence that rapidly rotating strongly magnetized neutron stars exist or can be made, and Appendix A argues against their formation.

Known rapidly rotating neutron stars (millisecond pulsars) have small magnetic moments $\mu \lesssim 10^{27}$ gauss-cm$^3$, and magnetic energy $\lesssim 10^{36}$ ergs, insufficient to power FRB even with unit efficiency. Their rapid rotation is attributed to “recycling” by accretion. In addition, a very rapidly rotating strongly magnetized neutron star drives away surrounding matter with its relativistic wind, so there may be no nearby particles to accelerate. Extrapolating its spindown backward in time indicates that the Crab pulsar was born with a period of about 17 ms, too slow for rotation to be significantly stabilizing, and there is no evidence that other neutron stars are born faster.

I therefore consider neutron star collapse produced by accretion. Accretion from binary companions powers many Galactic X-ray sources, permitting an estimate of the rate at which neutron stars will be pushed over their stability limit. A neutron star born with a mass of $1.2 M_\odot$ must accrete about $1 M_\odot$ to collapse (Antoniadis et al. 2013), consistent with the life expectancy and accretion rates of at least some X-ray binaries (Tauris & van den Heuvel 2006). The more massive ($\approx 2 M_\odot$) observed neutron stars may have been formed with those masses (requiring less accretion to collapse) or be the result of accretion so far insufficient for collapse.

9.1.1 Rate

An accreting neutron star in a binary system may accumulate mass until it exceeds its maximum mass, when it will rapidly collapse to a black hole. Such neutron stars emit their accretional energy as X-rays, so that the total rate of neutron star accretion in a galaxy is bounded by its X-ray luminosity (there are other contributors to X-ray luminosity, including supernova remnants and accreting black holes). If a mass $\Delta M$ must be accreted to push a neutron star over its maximum mass and the accretion energy per unit mass is $\epsilon c^2$ then the mean repetition time between collapses in a galaxy is

$$t_{\text{rep}} = \frac{\Delta M \epsilon c^2}{L_{\text{XNS}}}$$

(18)

where $L_{\text{XNS}}$ is the luminosity attributable to accretion onto neutron stars. For a nominal galactic $L_{\text{XNS}} = 10^{41}$ ergs/s (Kim & Fabbiano 2004), $\Delta M = 1 M_\odot$ and $\epsilon c^2 = 10^{36}$ ergs/g, $t_{\text{rep}} \sim 10^4$ y. This value may be barely consistent with the observed FRB rate of $\sim 10^4$/sky-yr. $L_{\text{XNS}}$ may be much greater in star-forming galaxies (Mineo, Gilfanov & Sunyaev 2012). For our Galaxy $L_{\text{XNS}} \approx 3 \times 10^{35}$ ergs/s (Kim & Fabbiano 2004) and $t_{\text{rep}} \sim 3 \times 10^4$ y.

This explains why collapse FRB are rare, and why their observed distribution is not dominated by a Galactic component. In this model FRB radiation cannot be collimated, for that would require a collapse rate much higher than the observed FRB rate, but the enormous energy available in collapse obviates the need for collimation. If an average could be taken over a time $t_{\text{obs}} \gg t_{\text{rep}}$ the Galactic plane would dominate the FRB sky just as it dominates the visible/IR sky (Sec 5), because in this model non-repeating FRB are products of stellar evolution.

9.1.2 Energetics

Relativistic MHD calculations (Lehner et al. 2012; Dionsyopoulou et al. 2013) of collapsing magnetized neutron stars in vacuum have indicated radiation at frequencies $\sim 10^3$ Hz of 5–16% of the initial magnetostatic energy. The external magnetostatic energy (ignoring relativistic effects) is $\mu^2/3\epsilon \approx 3 \times 10^{41} \mu_3^2$ ergs. To explain non-repeating FRB with estimated energies $\sim 10^{40}$ ergs by this process requires at least one of: 1) collimation (excluded by the argument of Sec. 9.1.1); 2) fairly efficient conversion of the collapse radiation to FRB; or 3) $\mu_3 \gg 1$.

Accreting neutron stars in binary systems, observed as X-ray sources, typically have magnetic moments $\mu \approx 10^{20}–10^{21}$ gauss-cm$^3$. The magnetic moments of SGR are believed (Katz 1982; Thompson & Duncan 1992, 1995) to be in the range $\mu = 10^{22}–10^{23}$ gauss-cm$^3$. Although no known SGR is in a binary system, this establishes the existence of neutron stars with extremely large magnetic moments and magnetostatic energies, some of which may have, perhaps later in their evolution, mass-transferring binary companions.

9.2 Collapsing White Dwarfs

Accretion-induced collapse (AIC) of white dwarfs to neutron stars has long been discussed as a possible origin of neutron stars and as a possible mechanism of supernovae. Many single magnetic white dwarfs are unusually massive, some with masses $> 1.3 M_\odot$ (Ferrario, de Martino & Gansicke 2015) that may be the result of dissolution of binary companions as their mass is transferred. “Polars” (synchronously rotating magnetic white dwarfs in mass transfer binaries) have been observed with fields up to 200 MG. Accretion-induced collapse of strongly magnetized white dwarfs is plausible, although no system is known in which such collapse can be predicted.

9.2.1 Rate

Accretion onto white dwarfs is $\sim 100$–1000 times less luminous than accretion onto neutron stars, the value of $\sim 100$ only applying at a radius of $\sim 10^6$ cm, near the threshold of collapse. As a result, measurements of the X-ray luminosity...
of galaxies do not constrain the rate of accretion-induced collapses of white dwarfs. Their low luminosity also makes it hard to identify candidate objects in our Galaxy.

9.2.2 Energetics

During pre-collapse contraction (a slow process resulting from the increase in mass) as well as dynamical collapse itself a frozen-in magnetic field increases $B \propto r^{-2}$, so the magnetic moment decreases $\mu \propto \mu_0 r/r_0$, where $\mu_0$ and $r_0$ are the initial moment and radius. This changing dipole moment radiates during dynamic collapse, principally at its end, as the star approaches neutron star density. At a radius $r$, time scale $\Delta t \sim r/v$, where $v$ is the infall speed, and frequency $\omega \sim 1/\Delta t$, the radiated energy

$$\mathcal{E} \sim \frac{\omega^2 \mu^2}{3c^3} \Delta t \sim \frac{\mu_0^2 r_0^2}{3r (c\Delta t)^3} \sim \frac{\mu_0^2}{c} \left(\frac{v}{c}\right)^2 \frac{1}{3c\Delta t}.$$  (19)

If the field is frozen in during the pre-collapse quasi-static evolution of the white dwarf, $\mu_0$ and $r_0$ may have the values observed in magnetic white dwarfs of $\mu_0 \sim 10^{35}$ gauss-cm$^3$ and $r_0$ as small as $5 \times 10^8$ cm. Rare, as yet unobserved, objects may have larger ratios $\mu_0/r_0$.

Non-repeating FRB with width $\Delta t \sim 1$ ms must be produced in the last ms (or less) of the collapse. Farah, Flynn, Bailes et al. (2018); CHIME/FRB (2019a) reported non-repeating FRB with $\Delta t \sim 0.1$ ms, a brevity previously only found in repeating FRB (Michilli et al. 2018), although it is not impossible that these ultra-short events are repeating FRB whose repetitions have not been observed. In the final stages of collapse $v \sim 0.5c$, so that

$$\mathcal{E} \sim 10^{44} \left(\frac{\mu_0}{2 \times 10^{35}\text{gauss-cm}^2}\right)^2 \frac{1 \text{ms}}{\Delta t} \text{ergs},$$  (20)

providing enough low frequency (kHz) energy to power the most energetic ($\sim 10^{40}$ ergs) FRB even with a low ($\sim 10^{-4}$) efficiency of conversion to GHz radiation.

9.3 Time Scale

For either collapse model to explain non-repeating FRB, not only must the low frequency (kHz) radiation produced by the changing dipole moment of the collapsing object be emitted within the brief duration of the FRB, but so must the GHz radiation defining the FRB itself. This might seem to require an emission region of size $< c\Delta t \sim 3 \times 10^6 \times 3 \times 10^6$ cm, corresponding to $\Delta t \sim 0.1$–1 ms. This would be an objection to this hypothesis because it would require the presence of radiating matter with a region that had (as part of a collapsing white dwarf) presumptively collapsed to the neutron star, or (as part of a collapsing neutron star) had been inside a plausible accretion disc.

Instead, I suggest that when the energetic (Eq. 20) pulse of dipole radiation encounters surrounding matter particles are accelerated in the direction of the Poynting vector, radially outward. At a radius $R$ particles of Lorentz factor $\gamma$ effectively radiate to the observer only from a patch of width $\sim R/\gamma$, and the resulting $\Delta t \sim R/(c^2\gamma^2)$. This cannot be evaluated quantitatively without an estimate of $\gamma$, but is consistent with $R$ comparable to the size of mass transfer binaries ($R \sim 10^{17}$ cm) if $\gamma \sim 10^2$.

10 CONCLUSIONS

Two models are required, one for repeating FRB and another for non-repeating FRB, that appear to be different phenomena. This is inferred from several arguments, the most compelling of which are duty factors and rotation measures (Michilli et al. 2018), each of which differ by at least three orders of magnitude between the repeaters and apparent non-repeaters. The second repeater (CHIME/FRB 2019b) may soon provide a test of this inference if its duty factor and rotation measure are measured. The two models are distinct, one involving accreting black holes to describe repeating FRB and the other, that can explain only non-repeating FRB, involving neutron star or white dwarf collapse.

In the model of repeating FRB, they are produced by the highly collimated emission of very relativistic electrons accelerated by magnetic reconnection, as discussed in Sec. 6. This may occur in shear flows in jets accelerated by accretion onto massive black holes. Accretion disc and their jets are long-lived and fluctuate, consistent with the long life and episodic behavior of the repeating FRB 121102. This model builds on elements of earlier speculations that FRB are wandering narrow beams (Katz 2017a) and that they are associated with intermediate mass black holes (Chatterjee et al. 2017; Marcote et al. 2017; Katz 2017c). Because the electromagnetic energy in accretion discs is high, GHz radiation cannot propagate through them, and must be produced in and escape through the low density relativistic jet.

The distribution of non-repeating FRB on the sky implies either that they are not associated with a stellar population or that they are rare, energetic and singular events, none of which have occurred in the Galaxy in the regions and during the time in which they could have been observed. This distinguishes them from phenomena, like the giant pulses of pulsars or the outbursts of the repeating FRB 121102, that have a broad distribution of strengths and whose energy output is dominated by the weakest events.

The absence of repetitions during the monitoring of “non-repeating” FRB sets an upper bound on their mean repetition rate. If repetitions are Poissonian this upper bound is a few times the reciprocal of the characteristic interval time of FRB 121102 of 60 s (Fig. 1) because of the lower detection threshold (about 40 Jy-ms); if these sources do repeat, the repetition rate would be higher for lower thresholds unless they are standard flares. It also cannot be directly compared to the characteristic interval time of FRB 121102 of 60 s (Shannon et al. 2018) should be interpreted with caution because of its high detection threshold of about 40 Jy-ms; if these sources do repeat, the repetition rate would be higher for lower thresholds unless they are standard flares. It also cannot be directly compared to the characteristic interval time of FRB 121102 of 60 s (Fig. 1) because of the lower detection threshold (about 40 Jy-ms) and different frequency (4-8 GHz) of Zhang et al. (2018). If repetitions are positively correlated (as they are in FRB 121102) the upper bound on the mean repetition rate is even less, its value depending on the shape of the correlation function, but if they are anti-correlated it could be relaxed.

Collapsing white dwarfs and neutron stars are distributed throughout galaxies as were their progenitors, Population I stars. As a result, a large RM like that of PSR J1745–2900 in the region around a galactic nucleus like Sgr A* is not expected, consistent with the comparatively low RM of non-repeating FRB (Michilli et al. 2018). This spatial distribution does not contradict the absence of FRB in the
Galactic plane (Sec. 5) because non-repeating FRB have a large characteristic strength and are very infrequent. In a sufficiently long time average the Galactic plane would dominate the non-repeating FRB sky (because of the proximity of Galactic FRB progenitors), but “sufficiently long” is longer than the interval between non-repeating FRB in a galaxy, ~10^7 yr. FRB described by this model do not repeat, will generally not be found in galactic nuclei, and are likely to be identified with galaxies and regions with rapid star formation. Their accompanying gravitational wave signal is weak because slowly rotating stars collapse almost spherically symmetrically.

The hypotheses and models presented here that repeating and apparently non-repeating FRB are fundamentally different phenomena predict that repeaters discovered in the future will qualitatively resemble FRB 121102 in several respects: Their bursts will be (compared to most non-repeating FRB) of low energy, they will have high but fluctuating rotation measure, if in galaxies of regular form they will in the host’s central region, they may be associated with weak (but not strong) persistent radio sources, some or all of their bursts will show downward spectral drifts, and their repetitions will not be periodic. It also predicts that extended observations will divide bursters into two distinct classes on the basis of their duty factor; apparent non-repeaters will either remain non-repeaters indefinitely or will repeat comparably frequently (of course, every repeater is first discovered as a single burst).

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It is possible to estimate the maximum angular spin rate $\omega_0$ of a neutron star newly formed by a core collapse supernova by equating the accretional torque with the spindown torque of a magnetic rotor immersed in a medium with Alfvén speed $v_A$:

$$M \ell \sim \frac{\omega^3 \mu^2}{v_A^3},$$  \hspace{1cm} (A1)

where $\ell = 10^{16} \text{cm}^2/\text{s}$ is the specific angular momentum of accreting matter and $v_A \sim B/\sqrt{\sigma} \sim \mu/\sqrt{M^3/\ell}$, where $\sigma$ is the formation of the neutron star the density $\rho \sim M/r^3$. This yields

$$\omega_0 \sim \left(\frac{M \mu}{M^3/2 r^3/2}\right)^{1/3}.$$  \hspace{1cm} (A2)

The accretion rate $M \sim M/t_{\text{acc}}$, where the accretion time is poorly known. The rise rate of the SN1987A neutrino flux indicates that $t_{\text{acc}} < 0.2 \text{s}$, but this estimate is limited by the low count rate and $t_{\text{acc}}$ could be much less than the indicated upper bound. Numerically, taking $r = 10^6 \text{cm}$, the final neutron star radius, to maximize $\omega_0$,

$$\omega_0 \sim \left(\frac{\mu_0}{t_{\text{acc}} \sim 3}\right)^{1/3} 60 \text{s}^{-1},$$  \hspace{1cm} (A3)

where $\mu_0 \equiv \mu/10^{30} \text{gau}\text{s-cm}^3$ and $t_{\text{acc}} \equiv t_{\text{acc}}/10^{-3} \text{s}$. This rate is several times less than the inferred original spin of the Crab pulsar $\omega_0 \approx 400 \text{s}^{-1}$, but is consistent with the longer initial periods indicated by statistical studies of pulsars (Noutsos et al. 2013). Fullback may further spin up the star, but this crude estimate is an argument against the suggestion of neutron stars born spinning near break-up, as required in pulsar models of repeating FRB (Katz 2018a).

**APPENDIX B: DUTY FACTOR**

Assume a power law distribution of spectral densities $S$

$$\frac{dN}{dS} = f S^{1-\beta}.$$  \hspace{1cm} (B1)

The number of temporal intervals in an observation of duration $T$ and temporal resolution $\Delta t$ with flux density $S$ greater than a threshold $S_{\text{min}}$ (corresponding to the number of bursts if they are not temporally resolved, or if the resolution is artifically broadened to avoid resolving them) is, if $\beta > 1$,

$$N = \frac{T}{\Delta t} \int_{S_{\text{min}}}^{\infty} \frac{dN}{dS} dS = \frac{T}{\Delta t} \frac{f}{1-\beta} S_{\text{min}}^{1-\beta}.$$  \hspace{1cm} (B2)

Setting $N = N_b$, the number of observed bursts

$$f = N_b \frac{\Delta t}{T} S_{\text{min}}^{1-\beta}.$$  \hspace{1cm} (B3)

The expected brightness of the brightest burst may be estimated by taking $N = 1$ in Eq. B2:

$$S_{\text{max}} \sim S_{\text{min}} N_b^{1/(\beta-1)}$$  \hspace{1cm} (B4)

and the typical brightness $S_0 \ll S_{\text{min}}$ in intervals in which no bursts are detected by taking $N = T/\Delta t$

$$S_0 \sim S_{\text{min}} \left(\frac{N_b}{T/\Delta t}\right)^{1/(\beta-1)}.$$  \hspace{1cm} (B5)

These extrapolations are only as good as the assumption of the power law distribution Eq. B1.

The means in Eq. 1 are taken over the time of observation (not over bursts), so that for $2 > \beta > 1$

$$\langle S \rangle = \int_{S_{\text{min}}}^{S_{\text{max}}} \frac{dN}{dS} S dS = N_b \frac{\Delta t}{T} 2 - \beta S_{\text{min}}^{(2-\beta)} - \beta S_{\text{max}}^{(2-\beta)}$$  \hspace{1cm} (B6)

and

$$\langle S^2 \rangle = \int_{S_{\text{min}}}^{S_{\text{max}}} \frac{dN}{dS} S^2 dS = N_b \frac{\Delta t}{T} 3 - \beta S_{\text{min}}^{(3-\beta)} - \beta S_{\text{max}}^{(3-\beta)}.$$  \hspace{1cm} (B7)

Then

$$D = \frac{\langle S^2 \rangle}{\langle S \rangle^2} = \frac{\Delta t (\beta - 1)(3 - \beta)}{(2 - \beta)^2} \approx 10 \frac{\Delta t}{T},$$  \hspace{1cm} (B8)

for $\beta \approx 1.7$ (Gourdji et al. 2019; Lu & Piro 2019). These results assume that no bursts are observed with $\langle S \rangle$ much greater than the nominal $S_{\text{max}}$ (Eq. B4): the means $\langle S \rangle$ and $\langle S^2 \rangle$ are not properly defined for $\beta < 2$ and $\beta < 3$, respectively, because if their upper bounds are taken as infinity the integrals are dominated by rare strong outliers and diverge. However, most data realizations have no such outliers, justifying the imposition of the upper bound $S_{\text{max}}$ when considering a single finite data set.

This result is independent of the detection threshold $S_{\text{min}}$, so that results from different telescopes with different values of $S_{\text{min}}$ can be compared (provided the power law assumption is valid), as well as results obtained at different
frequencies. If more than one burst is observed then $D$ can be estimated, at least roughly, from the data. If only one burst is observed only an upper bound to $D$ exists and Eq. B8 can be used to interpret this as a rough lower bound on the repetition time $T$.

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