Are Fast Radio Bursts Markers of Dark Core Collapse?

J. I. Katz, 1⋆
1Department of Physics and McDonnell Center for the Space Sciences, Washington University, St. Louis, Mo. 63130 USA

ABSTRACT
Are some neutron stars produced without a supernova, without ejecting mass in a remnant? Theoretical calculations of core collapse in massive stars often predict this. The observation of the repeating FRB 121102, whose dispersion measure has not changed over several years, suggests that dark core collapses are not just failures of computer codes, but may be real. The existence of one repeating FRB with unchanging dispersion measure is not conclusive, but within a decade hundreds or thousands of FRB are expected to be discovered, likely including scores of repeaters, permitting useful statistical inferences. A naïve supernova remnant model predicts observable decline in dispersion measure for 100 years after its formation. If an upper limit on the decline of 2 pc/cm$^3$ is set for five repeating FRB, then the naïve model with nominal parameters is rejected at the 95% level of confidence. This may indicate dark neutron star formation without a supernova or supernova remnant. This hypothesis may also be tested with LSST data that would show, if present, a supernova at an interferometric FRB position if it occurred within the LSST epoch.

Key words: radio continuum: general, stars: supernovæ: general

1 INTRODUCTION
For several decades, many calculations of core collapse of massive stars have failed to yield the expected result, an explosion explaining observed core collapse supernovæ (Janka 2017; Müller 2017; Soker 2017). Much effort has gone into improving the calculations to explain the core collapse supernovæ that surely exist. Yet this conundrum can be viewed differently: The naïve calculations may be predicting a real phenomenon, the formation of neutron stars without a visible supernova and without expulsion of a envelope forming a supernova remnant.

We certainly know of core collapse supernovæ that birthed neutron stars, for their remnants are visible, and some of the supernovæ themselves were observed in historic times. Dark neutron star formation is harder to demonstrate. If we observe a neutron star, typically a radio pulsar but in some instances a thermal X-ray source, soft gamma repeater/anomalous X-ray pulsar or a gamma-ray pulsar, the absence of a surrounding supernova remnant may be attributed alternatively to dissipation of an older remnant or to dark neutron star formation. Demonstrating dark neutron star formation would require confidence that the neutron star is younger than any plausible dissipation time of a remnant, one or a few thousand years. Pulsar spindown times set upper bounds on neutron star ages, but no pulsar with such a short spindown time is known to lack a supernova remnant.

The recent discovery (Spitler, et al. 2016; Scholz, et al. 2016; Chatterjee, et al. 2017; Marcote, et al. 2017) of the repeating FRB 121102 offers another approach to finding young neutron stars without supernova remnants. Over a period of about three years the dispersion measure (DM) of this FRB has not changed by more than about 5 pc/cm$^3$. Energetic arguments (Katz 2016) indicate that FRB are associated with young neutron stars, although it is unclear whether these resemble pulsars, soft gamma repeaters, or some novel class. Murase, Kashiyama & Mezåros (2016); Piro (2016); Kashiyama & Murase (2017); Metzger, Berger & Margolit (2017) have considered the constraints that can be placed on the parameters of a supernova remnant in which FRB 121102 may be embedded. Piro & Burke-Spolaor (2017) suggested that FRB 110220 and 140514, that have consistent positions, represent a repeating FRB whose DM drastically decreased over three years as a result of the remnant’s expansion. Most authors assume a very massive remnant, typically scaling their results to a mass of $10 M_\odot$. Beloborodov (2017) and Dai, Wang & Yu (2017) suggested that FRB 121102 and the apparently associated steady radio source (Chatterjee, et al. 2017) are produced in a pulsar wind nebula without a confining supernova remnant. Dai, Wang & Yu (2017) suggested several possible mechanisms for producing such an object, most of which involve separating a neutron star from its natal supernova

⋆ E-mail: katz@wuphys.wustl.edu

© 2017 The Authors
remnant, but also including accretion-induced collapse of a white dwarf (Canal & Schatzman 1976; Nomoto & Kondo 1991) without expulsion of debris. This proposed mechanism of dark neutron star formation may be disapproved by the known association of accreting white dwarfs with SN Ia.

This note considers the hypothesis that FRB are produced by young neutron stars formed darkly, without a supernova or a supernova remnant. Perhaps some accretion-induced collapses of white dwarfs do not lead to thermonuclear explosions. Alternatively, I hypothesize that some core collapses produce a neutron star without a supernova and without an expanding remnant.

Within a decade it is likely hundreds or thousands of FRB will be observed, including scores of repeaters if they have the same abundance as in the present database. This will permit statistical studies of any variation in dispersion measure; a single repeater with constant dispersion measure may be a fluke, but if many such are observed the inference will be either that FRB occur in comparatively old neutron stars whose supernova remnants have dissipated, or that they are not accompanied by supernova remnants at all.

2 WHY DARK CORE COLLAPSE?

Two arguments, neither new, lead to the suggestion of dark neutron star formation. The first is the difficulty core collapse calculations (Janka 2017; Müller 2017; Soker 2017) have of explaining supernovae. If we didn’t know that core collapse supernovae actually exist, we would probably conclude that core collapses lead, depending on the mass of the collapsing star, either to a black hole or to a darkly formed neutron star. Decades of work on hydrodynamics and neutrino transport, together with inclusion of angular momentum, have led to calculated explosions, but this work has been motivated, and perhaps implicitly biased, towards that result. Hence it is plausible that neutron stars may be formed, without an explosion, from the core collapses of some stars below the neutron star upper mass limit; observationally, the star simply “winks out.”

The second argument is empirical. Most Galactic radio pulsars have space velocities of several hundred km/s (Lyne & Lorimer 1994). Their spatial distribution indicates that they are Population I objects, so they must acquire these velocities when the neutron stars are formed. Yet there are also pulsars and neutron star X-ray binaries (in fact, a superabundance) in globular clusters that have escape velocities of 10–20 km/s (Katz 1975). Only $\lesssim 10^{-4}$ of the phase space of the Galactic pulsar velocity distribution is at speeds low enough for a pulsar, or a binary containing it, to be retained in the globular cluster. Additional empirical evidence for neutron star formation with low recoil has been derived from studies of the double pulsar PSR J0737-3039 (Piran & Shaviv 2005; Dall’Osso, Piran & Shaviv 2014; Beniamini & Piran 2016; Beniamini, Hotokozaka & Piran 2016).

These globular cluster neutron stars must be produced in very different events, collapses that give very little recoil to the forming neutron star. An obvious candidate for such events is a dark core collapse; with no mass ejected, there is no mechanical recoil. Other recoil-inducing processes (anisotropic neutrino emission, interference of magnetic dipole and quadrupole radiation) must also be weak. It is unclear what properties of the progenitor determine which path (dark or explosive) its collapse will take.

3 NAÏVE MODEL, CAVEATS AND STATISTICS

The physics of supernova remnants is complex, even in their early phases, and impossible to predict quantitatively without much better knowledge of their parameters than is foreseeable. Significant processes include recollisions, shock reionization following collision with surrounding gas and photoionization by radiation from the neutron star (Metzger, Berger & Margalit 2017; Piro & Burke-Spolaor 2017). In order to estimate the feasibility of testing the hypothesis of dark neutron star formation by comparing it to expectations if a supernova remnant is present, we adopt a naïve model of the evolution of its contribution to the dispersion measure. If the model predicts an observable variation, then we may consider an absence of such variations in a large number of repeating FRB as evidence for dark neutron star formation. If there are also repeating FRB whose dispersion measures do vary (Piro & Burke-Spolaor 2017), that would be evidence for a bimodal character of their formation processes, analogous to the bimodal distribution of neutron star recoil velocities. From only one confirmed repeating FRB, it is not possible to form any firm conclusions, but the scores of repeating FRB discovered, it may be possible to form significant conclusions.

3.1 SNR model

A naïve model of dispersion by a supernova remnant assumes spherical symmetry. At early times interaction with interstellar matter is insignificant, and for a fully ionized ejecta mass $M \equiv M_{10} \times 10^{M_0}$ of cosmic composition ($(Z/A) = 0.85$; such a massive envelope is likely hydrogenic) expelled at a speed $v = v_0 \times 10^9$ cm/s, after a time $t \equiv t_9 \times 10^6$ s, the dispersion measure

$$DM = \frac{3f_{\text{geom}} M_4}{4\pi m_p c^2 t_9} \left\langle \frac{Z}{A} \right\rangle = 787 f_{\text{geom}} M_{10} \frac{t_9}{v_0^2} \text{pc-cm}^{-3},$$

where $f_{\text{geom}} = 1$ for a homogeneous sphere (with $v$ the expansion speed at its surface) and $f_{\text{geom}} = 1/3$ for a thin shell.

The remnant contribution to the FRB dispersion measure is not known because the intergalactic medium makes a

1 Observed supernova remnants are highly asymmetric, both on large angular scales (spherical harmonic indices 1, 2, 3, etc.) and on fine scales, visible as filaments (spherical harmonic indices $\gtrsim 100$). The dependence of electron column density on direction is unknown, and the naïve model describes its average. The problem is even more complex if velocities are nonradial, because then a filament can cross the line of sight as the remnant expands. Nonradial velocities that, following a point explosion, can only be produced by asymmetric deposition of energy or interaction with asymmetrically distributed circumstellar matter, increase the rate of change of dispersion measure and therefore strengthen any conclusions inferred from its upper bounds.
substantial, likely dominant, contribution whose magnitude is unknown (unless the FRB is associated with a galaxy with measured redshift). The unknown near-source environment and uncertain Galactic interstellar medium also contribute. However, the supernova remnant is likely the only significant source of the time derivative of the dispersion measure:

$$\dot{D}M = \frac{50f_{geom}M_{10}}{v^2 t^3_9} \text{ pc cm}^{-3} \text{y}^{-1}.$$  \hspace{1cm} (2)

or

$$t_9 = \left(\frac{50f_{geom}M_{10}}{\mid \dot{D}M \mid v^2_3} \right)^{1/3}.$$  \hspace{1cm} (3)

In Eq. 3 $|\dot{D}M|$ is expressed in pc/cm$^3$y. For FRB 121102 $|\dot{D}M| \lesssim 2 \text{ pc}/(\text{cm}^3\text{y})$ (Chatterjee, et al. 2017) and

$$t_9 \gtrsim 3 \left(\frac{f_{geom}M_{10}}{v_3} \right)^{1/3};$$  \hspace{1cm} (4)

its age is $\gtrsim 100$ y if the dimensionless variables are $\sim 1$.

If FRB 121102 is this old then its rotation rate will not slow by more than $\sim 30\%$ over the next century, and its FRB activity may remain roughly the same as it is today. However, we cannot exclude activity varying (but not systematically decaying) on shorter timescales, as observed for SGR that are several thousand years old.

Some of the plausible complications (Metzger, Berger & Margolit 2017) of this naïve model would have the effect of decreasing the bound in Eqs. 4 by providing additional contributions to $\dot{D}M$. For example, recombination of an ionized remnant would make $\dot{D}M$ more negative, mimicking and adding to the effect of expansion, while shock or photo-ionization would oppose the effect of expansion, possibly leading to $\dot{D}M > 0$. A recombined remnant would contribute nothing to $\dot{D}M (M_{10} = 0)$, and its $\dot{D}M = 0$.

### 3.2 Spindown regimes

An elementary calculation shows that there are two spindown regimes, depending on the magnitude of the magnetic dipole moment $\mu$. We assume that $\mu$ is constant and use the dipole radiation expression with $\mu \perp \varpi$. If

$$\mu > \sqrt{\frac{3 I c^3}{4 \varpi^2 t}},$$  \hspace{1cm} (5)

where $I \approx 10^{45}$ g cm$^2$ is the neutron star moment of inertia and $\omega = \omega_4 \times 10^9$ s$^{-1}$ is its present angular spin rate. Integrating the spindown equation yields, if $\omega \ll \omega_{birth}$, the present spin-down power

$$P = 3I^2c^3 \frac{\mu^2}{8 \mu^2 t^2} < \frac{1 \times 10^{37}}{B_{15}^2} \text{ ergs/s},$$  \hspace{1cm} (6)

where $\mu = 10^{33} B_{15}$ gauss cm$^3$. Substituting from Eq. 5,

$$P < \frac{1 \omega_4^2}{2} = 2 \times 10^{33} \frac{\omega_4^2}{t_{100}} \text{ ergs/s}. \hspace{1cm} (7)$$

For smaller values of the magnetic moment

$$\mu < \sqrt{\frac{3 I c^3}{4 \varpi^2 t}},$$  \hspace{1cm} (8)

the spin rate $\omega \approx \omega_{birth}$ and, using Eq. 8,

$$P = 2 \frac{\mu^2 \omega_4^4}{3 c^3} < \frac{1 \omega_4^2}{2} = 2 \times 10^{33} \frac{\omega_4^2}{t_{100}} \text{ ergs/s}, \hspace{1cm} (9)$$

identical to Eq. 7.

The unsurprising result that $P < \frac{1 \omega_4^2}{2}$, where $t$ is the neutron star’s age, is consistent with the power observed for FRB 121102, if both $\mu$ and $\omega$ be close to their optimal values. That might seem implausible, but there is a strong selection effect favoring detection of sources with optimal parameters$^2$. These conditions are relaxed if the radiation is beamed (Katz 2017a) or if energy storage (Katz 2017b) frees FRB from the limit of the spindown power. The ages of FRB that have not been observed to repeat is unknown, and may be very much shorter, permitting much greater powers.

### 4 STATISTICS OF $\dot{D}M$

When many repeating FRB are discovered statistical inference may become possible. From Eq. 2 we find the distribution of $\dot{D}M$:

$$\frac{dN}{d\dot{D}M} \propto \frac{dt}{\dot{D}M} = \frac{39}{3} \left(\frac{f_{geom}M_{10}}{v_3} \right)^{1/3} \left(\dot{D}M \right)^{-2/3} \text{pc}^2/\text{y}^2,$$  \hspace{1cm} (10)

If the intrinsic rate of FRB activity does not change as the supernova remnant ages and expands (so there is no selection effect favoring younger objects) then the distribution of $\dot{D}M$ is

$$\frac{dN}{d\dot{D}M} \propto \frac{dt}{\dot{D}M} = \frac{39}{3} \left(\frac{f_{geom}M_{10}}{v_3} \right)^{1/3} \left(\dot{D}M \right)^{-2/3} \text{pc}^2/\text{y}^2.$$  \hspace{1cm} (11)

The assumptions (no evolution of the FRB, the naïve SNR model and the absence of any correlation between FRB properties and the SNR parameters) may be tested with a measured distribution of $\dot{D}M$. Nonzero $|\dot{D}M|$ is detectable if $|\dot{D}M| > |\dot{D}M|_{thresh}$. The detection threshold $|\dot{D}M|_{thresh}$ is determined by the accuracy of $\dot{D}M$ measurements, the number of bursts observed, and the duration of the observational baseline. $|\dot{D}M|_{thresh} \approx 2 \text{ pc}/\text{cm}^3\text{y}$ with about three years of data.

This corresponds to a maximum age $t < \frac{100(f_{geom}M_{10}/v_3)^{1/3}}{\dot{D}M|_{thresh}}$ (Eq. 3) for which $|\dot{D}M| > |\dot{D}M|_{thresh}$. If FRB are active for a lifetime $T < t$, then all should show measurable non-zero $\dot{D}M$ (in contrast to FRB 121102). If $T > t$ the fraction

$$F(\dot{D}M < 0) = \frac{t}{T} \approx \frac{100y}{t_{100}} \left(\frac{f_{geom}M_{10}}{v_3} \right)^{1/3}$$  \hspace{1cm} (12)

are predicted to show measurable non-zero $|\dot{D}M| > |\dot{D}M|_{thresh}$. This is a testable consequence of the naïve supernova remnant model, and its empirical disproof would be evidence of dark neutron star formation.

Accidental cancellation of $\dot{D}M < 0$ by a positive contribution (ionization of a recombined remnant) is possible.

$^2$ This is the same argument that supports the assumption of energy equipartition between field and particles in incoherent synchrotron sources.
yielding $|\Delta M| < |\Delta M|_{\text{thresh}}$, but unlikely. If it occurs then some other FRB would be expected to have $\Delta M > 0$ because accurate cancellation of two contributions of opposite signs must be fortuitous.

If FRB are isotropic radiators without energy storage, then $T$ is limited (Katz 2017a) by the requirement of producing peak powers that for some FRB are $\sim 10^{43}$ ergs/s. Using the most optimistic estimates from Sec. 3.2, $T \lesssim 200$ yr, and this argument predicts that $\gtrsim 50\%$ of repeating FRB should show nonzero $\Delta M$ in a few years of observation. If this is not so, which would be established at 95\% significance if the first five repeaters with a few years of data all showed $\Delta M = 0$ to the accuracy of measurement, then one or more of the assumptions of the naïve model would be falsified. We suggest as a candidate to be rejected the assumption $M_{19} \neq 0$; if $M_{19} = 0$ then $\Delta M = 0$. This would imply either dark neutron star formation, with no supernova remnant (or supernova), or a recombined remnant.

5 LSST—VERY RECENT SN?

The Large Synoptic Survey Telescope (LSST Science Collaborations 2009) will accumulate a decade of observations over more than half the sky with a cadence of about once per two days (season and moonlight permitting) to a magnitude of $r \sim 27.5$. This will be sufficient to detect Type II supernovae (of absolute magnitude $-17$ and apparent magnitude about 25.5 at a luminosity distance of 3 Gpc) if they are at the arc-second position of a repeating FRB, determined interferometrically. Searching for such supernovae will test the hypothesis of dark FRB formation within the epoch of the LSST database.

The discovery of such a supernova would immediately determine the age of the neutron star making the FRB, and would disprove (at least for that FRB) the hypothesis of dark formation. That hypothesis is falsifiable, but its truth cannot be demonstrated.

6 DISCUSSION

The constancy over more than three years of the dispersion measure of the repeating FRB 121102 places strong constraints on any supernova remnant surrounding it. In a naïve model of a core collapse supernova remnant this leads to an approximate lower bound on its age of $\sim 100$ yr. A similarly naïve model of FRB as giant pulsar pulses, implausibly assuming 100\% efficient conversion of rotational energy to the coherent FRB pulse, indicates ages of the neutron star in more energetic FRB of $\lesssim 200$ yr and $\lesssim 2 \times 10^4$ yr in FRB 121102. More plausible values $\ll 1$ of efficiency lead to contradictions with ages implied by the naïve supernova remnant model.

These numbers are sufficiently uncertain that contradiction is avoidable, provided that implausibly high (much higher than observed in pulsars) efficiency of conversion of rotational energy to coherent radiation is allowed, or other loopholes (narrowly beamed radiation, energy storage) are considered. Still, the constancy of the dispersion measure of FRB 121102 suggests that no supernova remnant surrounds it. That would imply dark neutron star formation, a hypothesis that makes other testable predictions: the constancy of the dispersion measure of other repeating FRB and the absence of supernovae in LSST observations of the locations of FRB.

REFERENCES

Beloborodov, A. M. 2017 arXiv:1702.08644.
Beniamini, P., Hotokazaka, K. & Piran, T. 2016 ApJ 829, L13.
Beniamini, P. & Piran, T. 2016 MNRAS 456, 4089.
Canal, R. & Schatzman, E. 1976 A&A 46, 229.
Chatterjee, S., Law, C. J., Wharton, R. S. et al. 2017 Nature 541, 58.
Dai, Z. G., Wang, J. S. & Yu, Y. W. 2017 arXiv:1702.05831.
Dall’Osso, S., Piran, T. & Shaviv, N. MNRAS 438, 1005.
Janka, H.-Th. 2017 arXiv:1702.08825.
Katz, J. I. 1975 Nature 253, 698.
Katz, J. I. 2016 Mod. Phys. Lett. A 31, 1630013.
Katz, J. I. 2017a MNRAS in press arXiv:1611.01243.
Katz, J. I. 2017b MNRAS submitted arXiv:1702.02161.
Kashiyama, K. & Murase, K. 2017 arXiv:1701.04815.
Lyne, A. G. & Lorimer, D. R. 1994 Nature 369, 127.
LSST Science Collaborations 2009 arXiv:0912.0201.
Marcote, B., Paragi, Z., Hessels, J. W. T. et al. 2017 ApJ 834, L8.
Metzger, B. D., Berger, E. & Margolit, B. 2017 arXiv:1701.02370.
Müller, B. 2017 arXiv:1702.06940.
Murase, K., Kashiyama, K. & Mésáros, P. 2016 MNRAS 461, 4498.
Nomoto, K. & Kondo, Y. 1991 ApJ 367, L9.
Piran, T. & Shaviv, N. J. 2005 Phys. Rev. Lett. 94, 1102.
Piro, A. L. 2016 ApJ 824, L32.
Piro, A. L. & Burke-Spolaor, S. 2017 ApJ submitted arXiv:1703.03013.
Scholz, P., Spitler, L. G., Hessels, J. W. T. et al. 2016 ApJ 833, 177.
Soker, N. 2017 arXiv:1703.03673.
Spitler, L. G., Scholz, P., Hessels, J. W. T. et al. 2016 Nature 531, 202.

This paper has been typeset from a \TeX/\LaTeX file prepared by the author.