

A universal EDF for repeating fast radio bursts?

Wenbin Lu^{1*}, Pawan Kumar^{1†}

¹*Department of Astronomy, University of Texas at Austin, Austin, TX 78712, USA*

10 March 2022

ABSTRACT

Assuming: fast radio bursts (FRBs) are produced by neutron stars at cosmological distances; FRB rate tracks the core-collapse supernova rate; and all FRBs repeat with a universal energy distribution function (EDF) $d\dot{N}/dE \propto E^{-\beta}$ with a cutoff at burst energy E_{\max} . We find that observations so far are consistent with a universal EDF with $1.5 \lesssim \beta \lesssim 2.2$, high-end cutoff $E_{\max}/E_0 \gtrsim 30$ and normalization $\dot{N}_0 \lesssim 2 \text{ d}^{-1}$; where \dot{N}_0 is the integrated rate above the reference energy $E_0 \simeq 1.2 \times 10^{39} f_r^{-1} \text{ erg}$ (f_r is the radio emission efficiency). Implications of such an EDF are discussed.

Key words: radio continuum: general — stars: neutron

1 INTRODUCTION

Fast radio bursts (FRBs) are bright millisecond flashes mostly found at high Galactic latitudes (Lorimer et al. 2007; Thornton et al. 2013). Since discovery, they have received a large amount of theoretical study on possible progenitors¹, burst mechanisms (e.g. Katz 2014; Cordes & Wasserman 2016) and potential usage to probe the intergalactic medium (IGM, McQuinn 2014; Zheng et al. 2014) and cosmology (Gao et al. 2014). The strongest argument for their cosmological origin is that the large dispersion measures (DMs), the line-of-sight electron column density $DM = \int n_e dl \sim 10^3 \text{ pc cm}^{-3}$, are inconsistent with being from the average interstellar medium (ISM), stellar corona, HII regions and supernova remnants (SNRs) in the Galaxy (or even the Local Group, Kulkarni et al. 2014; Luan & Goldreich 2014). The fact that FRB 121102 has been observed to repeat (Spitler et al. 2016; Scholz et al. 2016) rules out catastrophic events at least for this burst.

FRB models are mostly based on neutron stars (NSs), which could naturally accommodate the short durations $\Delta t \lesssim 1 \text{ ms}$, bright coherent emission, repetitivity on a range of intervals ($\sim 10^2$ to 10^5 s or longer, depending on the flux level). In addition, many FRBs show pulse widths of $W \sim 1(\nu/\text{GHz})^{-4} \text{ ms}$ consistent with multi-path propaga-

tion spreading and are much longer than what intergalactic or Galactic scattering could account for (Macquart & Koay 2013; Katz 2016). This means the local plasma surrounding the progenitors must be more strongly scattering than the average ISM. The rotation measure given by the linearly polarized FRB 110523 is much larger than intergalactic or Galactic contributions, meaning the progenitor is located in a dense magnetized nebula (Masui et al. 2015). The DM from a SNR decreases with time, but the repeating FRB 121102 has a constant $DM \simeq 559 \text{ pc cm}^{-3}$ for 3 yrs. This means a possible NS must be older than $\sim 100 \text{ yr}$ and the DM from the SNR is smaller than $\sim 100 \text{ pc cm}^{-3}$ (Piro 2016). Therefore, FRBs are likely from NSs of 100 yr to 1 Myr old embedded in SNRs or star-forming regions.

Due to insufficient monitoring time, the other (so-far) “non-repeating” FRBs could also be repeating. In this *Letter*, we assume that FRBs are from NSs at cosmological distances and that they repeat with a universal energy distribution function² (EDF). Below, we first summarize the properties of FRB 121102 in section 2, and then explore the answers to the following questions: (I) *Do FRB statistics so far support a universal EDF? If so, what constraints can we put on it?* (II) *Is FRB 121102 representative of the ensemble?* (III) *What is the spacial density of FRB progenitors?*

2 FRB 121102

The isotropic equivalent energy of each burst is

$$E \approx 1.2 \times 10^{39} \frac{\mathcal{F}}{\text{Jy.ms}} f_r^{-1} D_{\text{Gpc}}^2 \Delta\nu_9 \text{ erg}, \quad (1)$$

² By “universal” we mean the probability distributions of the free parameters are well peaked.

* wenbinlu@astro.as.utexas.edu

† pk@astro.as.utexas.edu

¹ These models include: collapsing neutron stars (Falcke & Rezzolla 2014; Zhang 2014), mergers (Totani 2013), magnetars (Popov & Postnov 2010; Pen & Connor 2015; Katz 2015), giant pulses from young pulsars (Connor et al. 2016; Cordes & Wasserman 2016; Lyutikov et al. 2016), shocks (Lyubarsky 2014), flaring stars (Loeb et al. 2014), asteroids colliding neutron stars (Geng & Huang 2015; Dai et al. 2016). See Katz (2016) for a recent review.

where \mathcal{F} is the fluence, f_r is the radio emission efficiency, $D_{\text{Gpc}} = D \text{ Gpc}^{-1}$ is the luminosity distance³ and $\Delta\nu_9 = \Delta\nu \text{ GHz}^{-1}$ is the bandwidth of the FRB spectrum. The DM from IGM is given by (Inoue 2004)

$$DM(z) = \int_0^z \frac{cdz'}{H_0 \sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}} \frac{n_e(z')}{(1+z')^2} \quad (2)$$

and $n_e(z) = 2.1 \times 10^{-7} (1+z)^3 \text{ cm}^{-3}$ is the number density of free electrons. FRB 121102 has

$$DM = DM_{\text{tot}} - DM_{\text{Galaxy}} - DM_{\text{host}} \\ \simeq 559 - 188 - 100 = 271 \text{ pc cm}^{-3}, \quad (3)$$

which corresponds to redshift $z_0 \simeq 0.28$ and luminosity distance $D(z_0) \simeq 1.4 \text{ Gpc}$. The repeating rate above fluence $\mathcal{F}_0 = 0.5 \text{ Jy.ms}$ at 1.4 GHz is $\int_{\mathcal{F}_0} (\dot{N}/d\mathcal{F}) d\mathcal{F} \simeq 2 \text{ d}^{-1}$. The progenitor's time-averaged isotropic equivalent luminosity is

$$\dot{E} \simeq 6.5 \times 10^{34} f_r^{-1} D_{\text{Gpc}}^2 \Delta\nu_9 \text{ erg s}^{-1} \simeq 10^{35} f_r^{-1} \text{ erg s}^{-1}, \quad (4)$$

if we add up the total burst fluence of 3.1 Jy.ms during Arecibo⁴ Telescopes' on-source time 15.8 hr. The energy reservoir required to supply the bursting activity for a time $\tau = 10^3 \tau_3 \text{ d}$ is

$$E_{\text{tot}} \simeq 10^{43} f_r^{-1} \tau_3 \Omega_r / 4\pi \text{ erg}. \quad (5)$$

where Ω_r is the total sky coverage of all bursts from one progenitor. If FRBs are concentrated only in a narrow range of stellar latitude (e.g. poles), we have $\Omega_r \ll 4\pi$. The fluence distribution function of FRB 121102 is a power-law $dN/d\mathcal{F} \propto \mathcal{F}^{-1.78 \pm 0.16}$ (Wang & Yu 2016), so \dot{E} should mainly come from the most energetic bursts (which we missed due to insufficient monitoring time), and this is why eq.(5) is a lower limit. If the energy reservoir is the magnetosphere of a NS, it requires a magnetic field strength of $B \gtrsim 1.6 \times 10^{13} (\tau_3 \Omega_r / 4\pi f_r)^{1/2} \text{ G}$.

3 A UNIVERSAL LUMINOSITY FUNCTION

In this section, we assume FRB rate tracks the core-collapse supernova rate and that all FRBs repeat with a universal EDF. We calculate the detection rate of FRBs on the Earth as a function of source redshift, and then by comparing it with observations, we constrain the parameters of the EDF.

3.1 Model

Core-collapse supernova rate tracks the cosmic star-formation rate and is given by (Madau & Dickinson 2014)

$$\Phi_{\text{cc}}(z) = 2.8 \times 10^2 \frac{(1+z)^{2.7}}{1 + [(1+z)/5.9]^{5.6}} \text{ Gpc}^{-3} \text{ d}^{-1} \quad (6)$$

We assume that a fraction f_{frb} of NSs are able to produce observable FRBs and stay in the active phase for a local-frame time τ . During the active phase, a NS undergoes multiple ($\gtrsim 10^3$) bursts intermittently and we call it a ‘‘bNS’’, short

for ‘‘bursting neutron star’’. The EDF is assumed to be a power-law with a high-end cutoff⁵

$$\frac{d\dot{N}}{dE} = \begin{cases} \frac{(\beta-1)\dot{N}_0/E_0}{1-(E_{\text{max}}/E_0)^{1-\beta}} \left(\frac{E}{E_0}\right)^{-\beta}, & \text{if } E < E_{\text{max}}, \\ 0, & \text{if } E > E_{\text{max}}, \end{cases} \quad (7)$$

where E_0 is the reference burst energy corresponding to a fluence \mathcal{F}_0 when the source is at redshift z_0 and \dot{N}_0 is the integrated rate above E_0 . Without losing generality, we base the reference point (E_0, z_0 and \mathcal{F}_0) on FRB 121102

$$z_0 \simeq 0.28, \mathcal{F}_0 = 0.5 \text{ Jy.ms}, E_0 \simeq 1.2 \times 10^{39} f_r^{-1} \text{ erg}. \quad (8)$$

where z_0 has an uncertainty of $\sim 30\%$ (due to unknown DM_{host}), the uncertainty of E_0 mostly comes from z_0 (through eq. 1), and f_r is the radio emission efficiency. The statistics of FRB 121102 give $\dot{N}_0 \equiv \int_{E_0}^{\infty} (d\dot{N}/dE) dE \simeq 2 \text{ d}^{-1}$, but we keep the normalization constant \dot{N}_0 as a free parameter, since whether FRB 121102 is representative is to be determined. The other two free parameters ($\beta, \xi \equiv E_{\text{max}}/E_0$) are restricted in the ranges $\beta > 1$ and $\xi > 1$, because weaker bursts are more frequent and we have detected bursts with $E > E_0$.

Integrating over the cosmic volume, we get the all-sky detection rate above a fluence threshold \mathcal{F}_{th}

$$\dot{N}_{\text{det}}(\mathcal{F}_{\text{th}}) = f_{\text{frb}} \tau \int_0^{z_{\text{max}}} dz \frac{\Phi_{\text{cc}}}{1+z} \frac{dV}{dz} \int_{E_{\text{th}}(z)}^{E_{\text{max}}} \frac{d\dot{N}}{dE} dE, \quad (9)$$

where dV/dz is the differential comoving volume, $E_{\text{th}}(z)$ is the threshold energy above which bursts from a given redshift z are detectable

$$\frac{E_{\text{th}}(z)}{E_0} = \frac{\mathcal{F}_{\text{th}} D(z)^2}{\mathcal{F}_0 D(z_0)^2}, \quad (10)$$

and z_{max} is the given by $E_{\text{th}}(z_{\text{max}}) = E_{\text{max}}$. Combining eq.(6)–(10), we calculate the differential detection rate $d\dot{N}_{\text{det}}/dz$ as a function of redshift. We assume that the dimensionless quantity $f_{\text{frb}} \tau \dot{N}_0$ does not depend on redshift, so the normalized cumulative distribution of the all-sky event rate only depends on the two free parameters (β, ξ). We use χ^2 formalism to fit it with the observational normalized cumulative distribution of DM, i.e.

$$\left(\int_0^z \frac{d\dot{N}_{\text{det}}}{dz'} dz' \right)_n \text{ v.s. } \left(\int_0^{DM(z)} \frac{dN_{\text{obs}}}{dDM'} dDM' \right)_n \quad (11)$$

where $DM(z)$ is only the IGM component (eq. 2) and we use a constant host galaxy contribution⁶ $DM_{\text{host}} \equiv 100 \text{ pc cm}^{-3}$. The allowed parameter space in the (β, ξ) is determined by the significance probability $P(\chi^2/\text{dof})$.

On the other hand, by matching the normalization at

⁵ Since bursts 10 times dimmer than the reference fluence \mathcal{F}_0 have been observed from FRB 121102, a possible low-end cutoff could be at $E_{\text{min}}/E_0 < 10$. As can be seen later from eq.(10), such a low E_{min} will be observationally noticed only for very nearby sources at distances $D < 0.31 \text{ Gpc} \frac{D(z_0)}{1.4 \text{ Gpc}} \sqrt{\left(10 \frac{E_{\text{min}}}{E_0}\right) \left(2 \frac{\mathcal{F}_0}{\mathcal{F}_{\text{th}}}\right)}$, which corresponds to a $DM \lesssim 62 \text{ pc cm}^{-3}$. Current observations have found no FRBs below 200 pc cm^{-3} and hence put no constraint on the possible low-end cutoff.

⁶ We have also tested the case where $DM_{\text{host}} \equiv 0$ and the difference is small compared to the other uncertainties.

³ We use Λ CDM cosmology with $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.27$, and $\Omega_\Lambda = 0.73$.

⁴ The source is not simultaneously monitored by different telescopes, but Green Bank Telescope (S-band) gives a similar result $\dot{E} \simeq 3.2 \times 10^{34} f_r^{-1} D_{\text{Gpc}}^2 \Delta\nu_9 \text{ erg s}^{-1}$.

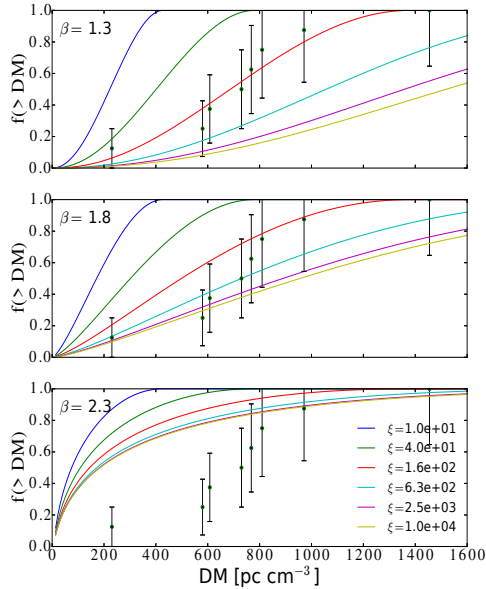


Figure 1. Comparison between normalized theoretical and observational FRB rate distributions. A fluence threshold $\mathcal{F}_{\text{th}} = 2$ Jy.ms is used.

a given β and ξ with the all-sky detection rate from observations, we calculate the product $f_{\text{frb}}\tau\dot{N}_0$, so the allowed parameter space in the β - ξ plane constrains $f_{\text{frb}}\tau\dot{N}_0$.

3.2 Observations

In the FRB search strategy (de-dispersion \rightarrow single-pulse search), the signal-to-noise ratio and hence detectability depends on both the fluence and de-dispersed pulse width as $S/N \propto \mathcal{F}W^{-1/2}$ (Keane & Petroff 2015). If there is a maximum intrinsic pulse width W_{max} , the threshold fluence for a given $(S/N)_0$ is $\mathcal{F}_{\text{th}} \propto (S/N)_0 W_{\text{max}}^{1/2}$. Keane & Petroff (2015) derive a completeness threshold of 2 Jy.ms for the Parkes FRBs. Therefore, we test our model only on Parkes FRBs with $\mathcal{F} > \mathcal{F}_{\text{th}} = 2$ Jy.ms, which converts to a sample of 8 bursts (Petroff et al. 2016).

Some other factors could introduce biases: (I) scattering by the Galactic ISM may bias against detection of FRBs at low Galactic latitudes (Burke-Spolaor & Bannister 2014; Petroff et al. 2014); (II) in de-dispersion trials, typically, DMs of $\lesssim 100$ and $\gtrsim 2000$ pc cm $^{-3}$ are not considered, resulting in effectively a low- (< 0.1) and high-redshift (> 2.5) blindness; (III) the source position within a single beam (FWHM $\simeq 15'$) is unknown and most authors use the on-axis assumption and report a lower limit.

Due to (I), we have discarded FRBs that occurred below Galactic latitude 20° . It turns out (II) does not introduce significant biases because the observed FRB are all between $0.25 < z < 1.4$ and the true rate should cut off sharply below and above this range. Based on (III), we also try the sample selected by $\mathcal{F}_{\text{th}} = 1$ Jy.ms (with 11 FRBs) for comparison.

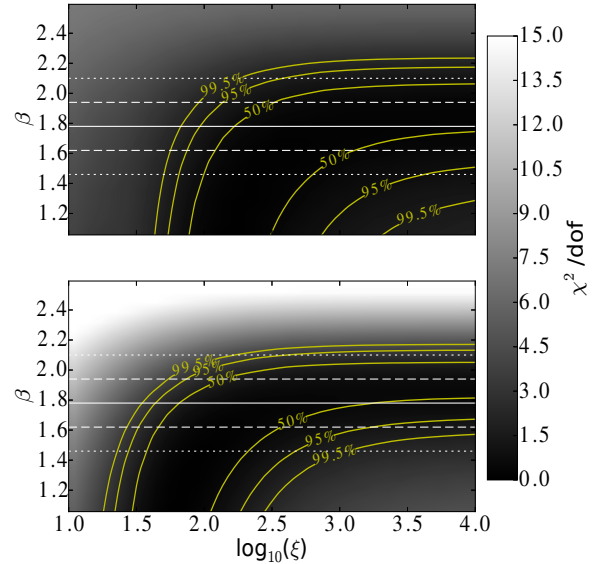


Figure 2. The reduced χ^2 of the fits between theoretical and observational FRB rate distributions. The upper and lower panels are for the two samples with $\mathcal{F}_{\text{th}} = 2$ and 1 Jy.ms respectively. The contours show the confidence levels. The power-law index for FRB 121102 $\beta = 1.78 \pm 0.16$ is marked by a white solid line, with 1- and 2- σ errors between dashed and dotted lines.

3.3 Results

In fig.(1), we compare the theoretical event rate above threshold $\mathcal{F}_{\text{th}} = 2$ Jy.ms with observations, for three different power-law slopes ($\beta = 1.3, 1.8, 2.3$) and various energy cutoffs ($\xi \equiv E_{\text{max}}/E_0$ from 10 to 10^4). We can see that, for a larger β and smaller ξ , more FRBs are expected to have small DM.

We quantify the goodness of the fit by calculating the reduced χ^2 , as shown in fig.(2). The upper panel is for $\mathcal{F}_{\text{th}} = 2$ Jy.ms (8 bursts) and the lower for $\mathcal{F}_{\text{th}} = 1$ Jy.ms (11 bursts). We can see that the two samples generally agree with each other and the allowed parameter space is

$$\{\beta \lesssim 2.2, \xi \gtrsim 10^{1.5}\}. \quad (12)$$

The bottom-right corner with $\{\beta \lesssim 1.4, \xi \gtrsim 10^3\}$ may be in tension with observations but the confidence level is not high and more data is needed. We also mark the power-law index for FRB 121102 $\beta = 1.78 \pm 0.16$, with 1- and 2- σ errors between dashed and dotted lines. The agreement with the constraints from the whole sample means that FRBs may indeed share a universal EDF. FRB 121102 may be representative in that its power-law index lies within the range allowed by the statistics from the whole population.

As for the normalization, we draw in fig.(3) the contours of

$$Q(\beta, \xi) = \log_{10} \left[f_{\text{frb}} \frac{\tau}{10^3 \text{ d}} \frac{\dot{N}_0}{1 \text{ d}^{-1}} \frac{10^4 \text{ Gpc}^3 \text{ d}^{-1}}{\dot{N}_{\text{det}}(\mathcal{F}_{\text{th}})} \right] \quad (13)$$

for the two samples with $\mathcal{F}_{\text{th}} = 2$ (upper) and 1 Jy.ms (lower panel). Dashed curves are for negative values. For the parameter space allowed by Parkes' data (red contours, eq. 12), we obtain $Q \in (-4.3, -2.7)$. The observa-

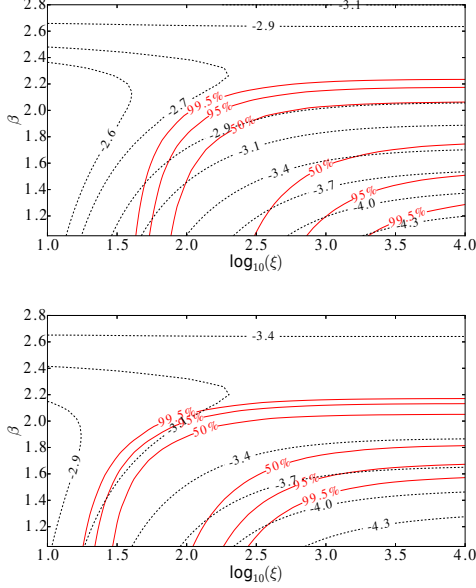


Figure 3. The contours of $Q(\beta, \xi)$ defined in eq.(13). The upper and lower panels are for the two samples with $\mathcal{F}_{\text{th}} = 2$ and 1 Jy.ms respectively. Red contours are the confidence levels from the χ^2 fitting of each sample.

tional all-sky FRB rate above ~ 2 Jy.ms is estimated to be $3 \times 10^3 - 1 \times 10^4$ Gpc $^{-3}$ d $^{-1}$ (Thornton et al. 2013; Keane & Petroff 2015; Rane et al. 2016; Champion et al. 2016). Considering all the uncertainties, we obtain

$$f_{\text{frb}} \frac{\tau}{10^3 \text{ d}} \frac{\dot{N}_0}{\text{d}^{-1}} \in (10^{-4.8}, 10^{-2.7}). \quad (14)$$

However, the normalization parameter \dot{N}_0 is still unconstrained so far and will be discussed in next section.

4 IS FRB 121102 REPRESENTATIVE?

Petroff et al. (2015) conducted a follow-up survey of the fields of 8 known FRBs⁷ and found none repeating. Other follow-up surveys, e.g. Ravi et al. (2015), are less constraining. For a given burst i at redshift z^i , the average number of repeating events above the threshold \mathcal{F}_{th} within a monitoring time ΔT^i is

$$\bar{N}_{\text{rep}}^i = \frac{\dot{N}_0 \Delta T^i / (1 + z^i)}{1 - \xi^{1-\beta}} \left[\left(\frac{\mathcal{F}_{\text{th}}}{\mathcal{F}_0} \right)^{1-\beta} - \xi^{1-\beta} \right]. \quad (15)$$

The probability of observing none of the 8 repeating is

$$P_0 = \prod_{i=1}^8 \exp(-\bar{N}_{\text{rep}}^i). \quad (16)$$

We take the monitoring time $\{\Delta T^i\}$ from Petroff et al. (2015) and assume that the survey is sensitive to any repeating bursts above the threshold $\mathcal{F}_{\text{th}} = 2$ Jy.ms. We calculate P_0 as a function of β and ξ from eq.(15) and (16) and show

⁷ They are not the same 8 bursts in the sample selected by $\mathcal{F}_{\text{th}} = 2$ Jy.ms as in Section 3.2 (only 3 of them overlap).

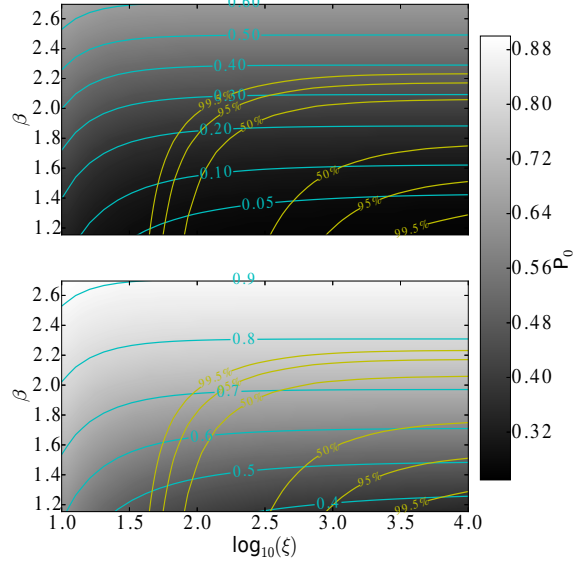


Figure 4. The probability of observing none of the 8 bursts repeating above the threshold $\mathcal{F}_{\text{th}} = 2$ Jy.ms. The upper and lower panels are for $\dot{N}_0 = 2$ and 0.5 d^{-1} respectively. Yellow contours are the χ^2 fitting confidence levels from the upper panel of fig.(2).

the result in fig.(4) for $\dot{N}_0 = 2$ (upper) and 0.5 d^{-1} (lower panel). We find that, if all FRBs repeat at the same rate as FRB 121102 ($\dot{N}_0 = 2 \text{ d}^{-1}$), the probability of observing none repeating is $P_0 \simeq 5\% - 30\%$. This, again, supports FRB 121102 as being representative of the whole population. Note that Petroff et al. (2015) used a relatively short cutoff of de-dispersed width $W \lesssim 8$ ms, which could lead to incompleteness above 2 Jy.ms and further increases P_0 .

On the other hand, Petroff et al. (2015) detected a new FRB at redshift $z \simeq 0.44$ in the survey. The average number of bNSs at redshift $\leq z$ in a sky area of $8 \times 0.5 = 4 \text{ deg}^2$ is

$$\bar{N}(z) = \frac{4 \text{ deg}^2 f_{\text{frb}} \tau}{4.1 \times 10^4 \text{ deg}^2} \int_0^z dz' \Phi_{\text{cc}}(z') (1 + z') \frac{dV}{dz'}. \quad (17)$$

The probability of having at least one bNS with $z \leq 0.44$ in the observed area is

$$P_{\geq 1} = 1 - \exp(-\bar{N}(0.44)) \simeq 1 - \exp(-1.6 f_{\text{frb}} \tau). \quad (18)$$

The product $f_{\text{frb}} \tau \dot{N}_0$ is constrained by eq.(14), so we have

$$\exp\left(-\frac{3.2 \text{ d}^{-1}}{\dot{N}_0}\right) < 1 - P_{\geq 1} < \exp\left(-\frac{2.5 \times 10^{-2} \text{ d}^{-1}}{\dot{N}_0}\right). \quad (19)$$

If every FRB repeats similarly as FRB 121102 ($\dot{N}_0 = 2 \text{ d}^{-1}$), the probability of having ≥ 1 FRBs at $z \leq 0.44$ in a 4 deg^2 area is $1.2\% < P_{\geq 1} < 80\%$, with lower \dot{N}_0 giving larger $P_{\geq 1}$.

Putting P_0 and $P_{\geq 1}$ together, we find the observations by Petroff et al. (2015) favor a normalization constant \dot{N}_0 smaller than the value of FRB 121102, but $\dot{N}_0 = 2 \text{ d}^{-1}$ is not ruled out at a high confidence. A relatively steep power-law with $\beta \in (1.5, 2.2)$ is also favored, as can be seen in fig.(4). Therefore, we conclude that FRB 121102 may be slightly more active than average (with a relatively large \dot{N}_0) but is so far consistent with being representative of the ensemble.

5 SUMMARY AND IMPLICATIONS FOR THE FRB PROGENITORS

This *Letter* is based on three hypotheses: (I) FRBs are produced by NSs at cosmological distances with their DMs mostly due to free electrons in the IGM; (II) FRB rate tracks core-collapse supernova rate; (III) FRBs repeat with a universal EDF $d\dot{N}/dE \propto E^{-\beta}$ with a high-end cutoff at E_{\max} . Based on these assumptions, we find that observations so far are consistent with a universal EDF with power-law index $1.5 \lesssim \beta \lesssim 2.2$, high-end cutoff $\xi \equiv E_{\max}/E_0 \gtrsim 30$ and normalization $\dot{N}_0 \lesssim 2 \text{ d}^{-1}$, where \dot{N}_0 is defined as the integrated rate above $E_0 \simeq 1.2 \times 10^{39} f_r^{-1} \text{ erg}$ (f_r being the radio emission efficiency). We also put constraints on the dimensionless product $f_{\text{frb}}(\tau/10^3 \text{ d})(\dot{N}_0/1 \text{ d}^{-1}) \in (1.6 \times 10^{-5}, 2.0 \times 10^{-3})$, where f_{frb} is the fraction of NSs that are able to produce observable FRBs and τ is the length of the bursting phase. Better statistics in the future could narrow down the uncertainties, if our hypotheses are correct. Some of the implications of our results on the FRB progenitors are as follows:

- The EDF of FRBs is shallower than the power-law tail of Crab giant pulses ($2.1 < \beta < 3.5$, Mickaliger et al. 2012) and consistent with magnetar bursts ($\beta \simeq 1.66$, Göğüş et al. 1999) and other avalanche events explained by Self-Organized Criticality (Lu & Hamilton 1991; Aschwanden et al. 2016).
- Burst energy can reach $E_{\max} \gtrsim 10^{41} f_r^{-1} \text{ erg}$, which is supported by the “Lorimer” burst with $E > 1.1 \times 10^{41} f_r^{-1} \text{ erg}$ (Keane & Petroff 2015).
- The spacial density of FRB progenitors is

$$f_{\text{frb}} \tau \Phi_{\text{cc}}(1+z) \in (64, 8000)(\dot{N}_0/1 \text{ d}^{-1})^{-1} \text{ Gpc}^{-3}, \quad (20)$$

where we have used $\Phi_{\text{cc}}(z=1)$ to get the numerical values. Although \dot{N}_0 still has large uncertainties, the fact the FRB 121102 is consistent with being representative means that \dot{N}_0 is likely not much smaller than 1 d^{-1} . If we want to use bNSs to probe the density fluctuations of IGM (McQuinn 2014), the spacial resolution may be $\gtrsim 50 \text{ Mpc}$.

- The fraction of NSs that are able to produce observable FRBs is $f_{\text{frb}} \in (1.6\text{e}-5, 2.0\text{e}-3)(\tau/10^3 \text{ d})^{-1}(\dot{N}_0/1 \text{ d}^{-1})^{-1}$. If we consider the possibility that $\tau \sim \text{kyr}$, the fraction could be as low as $f_{\text{frb}} \sim 10^{-6}$! Although the true fraction is a factor of $4\pi/\Omega_r$ higher (Ω_r is the total sky coverage of all bursts from one progenitor), FRB progenitors may be a rare type of NSs. For example, the birth rate of magnetars is $\sim 10\%$ of core-collapse rate (Keane & Kramer 2008), so “being a magnetar” may not be sufficient for FRBs.

6 ACKNOWLEDGMENTS

This research was funded by the Named Continuing Fellowship at the University of Texas at Austin.

REFERENCES

Aschwanden, M. J., Crosby, N. B., Dimitropoulou, M., et al. 2016, *Space Sci. Rev.*, 198, 47
 Burke-Spolaor, S., & Bannister, K. W. 2014, *ApJ*, 792, 19
 Champion, D.-J., Petroff, E., Kramer, M., et al. 2016, *MNRAS*

Cordes, J. M., & Wasserman, I. 2016, *MNRAS*, 457, 232
 Connor, L., Sievers, J., & Pen, U.-L. 2016, *MNRAS*, 458, L19
 Dai, Z. G., Wang, J. S., Wu, X. F., & Huang, Y. F. 2016, [arXiv:1603.08207](#)
 Falcke, H., & Rezzolla, L. 2014, *A&A*, 562, A137
 Gao, H., Li, Z., & Zhang, B. 2014, *ApJ*, 788, 189
 Geng, J. J., & Huang, Y. F. 2015, *ApJ*, 809, 24
 Göğüş, E., Woods, P. M., Kouveliotou, C., et al. 1999, *ApJL*, 526, L93
 Inoue, S. 2004, *MNRAS*, 348, 999
 Katz, J. I. 2014, *Phys. Rev. D*, 89, 103009
 Katz, J. I. 2015, [arXiv:1512.04503](#)
 Katz, J. I. 2016, *ApJ*, 818, 19
 Katz, J. I. 2016, [arXiv:1604.01799](#)
 Keane, E. F., & Kramer, M. 2008, *MNRAS*, 391, 2009
 Keane, E. F., & Petroff, E. 2015, *MNRAS*, 447, 2852
 Kulkarni, S. R., Ofek, E. O., Neill, J. D., Zheng, Z., & Juric, M. 2014, *ApJ*, 797, 70
 Loeb, A., Shvartzvald, Y., & Maoz, D. 2014, *MNRAS*, 439, L46
 Lorimer, D. R., Bailes, M., McLaughlin, M. A., Narkevic, D. J., & Crawford, F. 2007, *Science*, 318, 777
 Lu, E. T., & Hamilton, R. J. 1991, *ApJL*, 380, L89
 Luan, J., & Goldreich, P. 2014, *ApJL*, 785, L26
 Lyutikov, M., Burzawa, L., & Popov, S. B. 2016, [arXiv:1603.02891](#)
 Lyubarsky, Y. 2014, *MNRAS*, 442, L9
 Macquart, J.-P., & Koay, J. Y. 2013, *ApJ*, 776, 125
 Madau, P., & Dickinson, M. 2014, *ARA&A*, 52, 415
 Masui, K., Lin, H.-H., Sievers, J., et al. 2015, *Nature*, 528, 523
 McQuinn, M. 2014, *ApJL*, 780, L33
 Mickaliger, M. B., McLaughlin, M. A., Lorimer, D. R., et al. 2012, *ApJ*, 760, 64
 Pen, U.-L., & Connor, L. 2015, *ApJ*, 807, 179
 Petroff, E., van Straten, W., Johnston, S., et al. 2014, *ApJL*, 789, L26
 Petroff, E., Johnston, S., Keane, E. F., et al. 2015, *MNRAS*, 454, 457
 Petroff, E., Bailes, M., Barr, E. D., et al. 2015, *MNRAS*, 447, 246
 Petroff, E., Barr, E. D., Jameson, A., et al. 2016, [arXiv:1601.03547](#)
 Piro, A. L. 2016, [arXiv:1604.04909](#)
 Popov, S. B., & Postnov, K. A. 2010, *Evolution of Cosmic Objects through their Physical Activity*, 129
 Rane, A., Lorimer, D. R., Bates, S. D., et al. 2016, *MNRAS*, 455, 2207
 Ravi, V., Shannon, R. M., & Jameson, A. 2015, *ApJL*, 799, L5
 Scholz, P., Spitler, L. G., Hessels, J. W. T., et al. 2016, [arXiv:1603.08880](#)
 Spitler, L. G., Scholz, P., Hessels, J. W. T., et al. 2016, *Nature*, 531, 202
 Totani, T. 2013, *PASJ*, 65,
 Thornton, D., Stappers, B., Bailes, M., et al. 2013, *Science*, 341, 53
 Wang, F. Y., & Yu, H. 2016, [arXiv:1604.08676](#)
 Zhang, B. 2014, *ApJL*, 780, L21
 Zheng, Z., Ofek, E. O., Kulkarni, S. R., Neill, J. D., & Juric, M. 2014, *ApJ*, 797, 71