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Non-Cosmological FRBs from Young Supernova Remnant Pulsars

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ABSTRACT

We propose a new extragalactic but non-cosmological explanation for fast radio bursts (FRBs) based on very young pulsars in supernova remnants. Within a few hundred years of a core-collapse supernova the ejecta is confined within ∼1 pc, providing a high enough column density of free electrons for the observed 500-1500 pc/cm^3 of dispersion measure (DM). By extrapolating a Crab-like pulsar toDMs its infancy in an environment like that of SN 1987A, we hypothesize such an object could emit super-giant pulses sporadically which would be bright enough to be seen at a few hundred megaparsecs. In this scenario Faraday rotation at the source gives rotation measures (RMs) much larger than the expected cosmological contribution. If the emission were pulsar-like, then the polarization vector could swing over the duration of the burst, which is not expected from non-rotating objects. In this model, the scattering, large DM, and commensurate RM all come from one place which is not the case for the cosmological interpretation. The model also provides testable predictions of the flux distribution and repeat rate of fast radio bursts, and could be further verified by spatial coincidence with optical supernovae of the past several decades.

Key words: FRB, supernova remnants, pulsar, giant pulse

1 INTRODUCTION

The mystery of fast radio bursts (FRBs) has garnered substantial interest from the radio community. High-energy astrophysicists have tried to model their burst source, observers would like to measure a large population of them, and cosmologists hope to use them as a probe of the intergalactic medium (IGM). However their relative scarcity (only ∼ dozen have been observed so far) and their apparent transient nature have meant we still do not know their position on the sky to better than a few arcminutes, and their radial position could be anything from terrestrial to cosmological.

These objects are highly dispersed, with DMs (∼ 500-1200 pc/cm^3) far exceeding the expected contribution from our own galaxy's interstellar medium (ISM) and leading to the interpretation that FRBs are cosmological (Lorimer et al. 2007; Thornton 2013). Various emission mechanisms have been proposed at a wide range of source locations, including merging white dwarfs (Mickaliger et al. 2012) and neutron stars (Totani 2013), blitzars (Falcke & Rezzolla 2014), magnetars (Pen & Connor 2015; Lyubarsky 2014), and flaring Galactic stars (Loeb et al. 2014). Though presently there are more theoretical models for FRBs than actual sources discovered, constraints on such theories are rapidly emerging. This is due to recent polarization data, multifrequency coverage, and their being observed by several telescopes at various locations on the sky (Bower et al. 2014; Petroff 2014).

On top of event rates (∼10^4 per day per sky) and high DMs, explanations of FRBs must now account for temporal scattering, and polarization states. They should predict or explain Faraday rotation and time dependence of linear polarization. The rotation measure of our Galaxy has been mapped, and the intergalactic rotation measure is constrained to be less than 7 rad/m^2 (Oppermann et al. 2015).

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The observed temporal scattering is problematic for a IGM intepretation, due to the unrealistically small length scales required in the IGM for 1 ms scattering (Luan & Goldreich 2014).

In this letter we propose a new non-cosmological but extragalactic solution to the FRB problem: giant pulses from newly formed pulsars in supernova remnants (SNR's). The dense ionized environment of the SNR can provide 500-2000 pc/cm^3 of dispersion if the pulses are observed within ~ 100 years of the core-collapse supernova. In our picture the large DM and scattering all come from the same place, and generically accounts for substantial Faraday Rotation and polarization angle swings[1]. These are not expected in a cosmological interpretation of the DM.

2 SUPERNOVA REMANTS

Of order 10^{51} ergs of kinetic energy is released during a supernova, a fraction of which is converted into thermal energy after shock heating of the ejecta plasma. Though the shock-heated ejecta atoms are fully ionized after the explosion, the density is high enough that ionized atoms can soon recombine. This phase of low-ionization comes to an end when the remnant expands into the surrounding ISM, causing a reverse shock wave that reionizes the ejecta. Though this is the basic narrative, observations (Zanardo et al. 2014) as well as simulations (Potter et al. 2014) of SN 1987a have shown the morphological and ionization properties of SNR's in the decades and centuries after the explosion are nuanced and difficult to model. That said, in general the expanding nebula left behind should be able to provide enough free electrons along the line-of-sight for unusually large dispersion measures. If we assume a toy model in which a spherical shell expands at v_{ej}, then the radius R(t) $\approx v_{ej}t$. Therefore the DM we expect can be calculated as,

$$\mathrm{DM} \approx \frac{\mathrm{x}_e \mathrm{M_{ej}}}{m_p \frac{4\pi}{3} v_{\mathrm{ej}}^2 t^2} \tag{1}$$

where x_e is the ionization fraction, M_{ej} is the ejecta mass, and m_p is the mass of a proton. Assuming $\sim$10 $\mathrm{M}_\odot$ of material is ejected at $v_{ej} \sim 3 - 8 \times 10^3$ km/s and an ionization fraction of $\sim 20\%$, the dispersion measure goes from several thousand pc/cm^3 immediately after the reverse-shock ionization, to several hundred pc/cm^3 after 50-100 years. A similar treatment by Zanardo et al. (2014) found that a possible pulsar in SNR 1987a could have DMs between 100-6000 pc/cm^3, after ~ 25 years.

Another potentially important feature of the SNR environment is its magnetic field. The exact magnitude of any detection Faraday rotation has implications for the possible source location. For instance in the circumnuclear picture, one would expect rotation measures $\sim 10^{3-5}$ rad/m^2, similar to that of the Milky Way's Galactic center magnetar J1745-29. In the cosmological scenario, if the Faraday rotation came from the same place as the DM - namely the intergalactic medium - then we would only expect a few rad/m^2 of RM Oppermann et al. (2015).

[1] The authors disclose access to unpublished data prior to making these predictions

The Faraday effect rotates the polarization vector by an angle $\phi =$RM λ^2, where

$$\mathrm{RM} = \frac{e^3}{2\pi m^2 c^4} \int_0^L n_e(l) B_{\parallel}(l) dl \tag{2}$$

.

We can therefore make a rough estimate of the rotation measure of a remnant pulsar with dispersion measure DM. Using Burke & Graham-Smith (2014) we get,

$$\mathrm{RM} \approx 0.81\,\mathrm{rad}/m^2 \times \frac{\langle B_{\parallel} \rangle}{1\mu G} \cdot \frac{\mathrm{DM}}{1pc/cm^3} \tag{3}$$

.

Though there is a large uncertainty in evolution of the magnetic field strength and added uncertainty in $\langle B_{\parallel} \rangle$ given $B_{\parallel}$ is not necessarily positive, typical values in our galaxy are 0.2 - 1μG. For instance the Crab and Vela have $\sim 0.92\mu G$ and $\sim 0.56\mu G$, respectively. This gives RMs between $\sim 80 -$ 1200 rad/m^2 for a SNR pulsar with FRB-like DMs.

2.1 Event Rates

The daily FRB rate has been estimated at $3.3^{+5.0}_{-2.5} \times 10^3$ sky^{-1} (Rane et al. 2015). If we start from the local core-collapse supernova event rate, Γ_{CC}, and include objects out to some distance $d_{\max}$, we expect the following daily FRB rate,

$$\Gamma_{FRB} \sim \frac{4}{3}\pi d_{\max}^3 \times \Gamma_{\mathrm{CC}} \times \eta\, \tau_{\mathrm{ion}} \gamma_{\mathrm{GP}} \tag{4}$$

where τ_{ion} is the window in years when the SNR is sufficiently dense and ionized to provide the observed DMs and γ_{GP} is the daily rate of giant pulses brighter than ~ 500 mJy, and η is the number of core-collapse supernovae that leave behind a visible pulsar. From Taylor et al. (2014) we know $\Gamma_{CC} \sim 3 \times 10^{-4}$ day^{-1} $(h^{-1}\mathrm{Mpc})^{-3}$, so if we take d_{max} to be 100 h^{-1}Mpc and $\tau_{ion} \sim 100$ years, we require one giant pulse every 10-20 days, assuming one fifth of this SNe population leaves behind a visible pulsar. In Fig. 2.1 we show the event rate as a function of distance, varying two parameters: the effective high-DM window and the rate of giant pulses.

From Fig. 2.1 we can see even in our most conservative estimate, when the SNR only has a 25 year window and emits giant pulses once every 100 days, the volume necessary for the highest daily FRB rate is still non-cosmological. By this we mean the DM contribution from the IGM is less than ~ 200 pc/cm^3. If the SNR FRBs are within a hundred h^{-1}Mpc then DM$_{IGM}$ is less than $\sim 10\%$ of the total dispersion of a typical burst.

If FRBs really are giant pulses then they should repeat stochastically, and while none of the radio follow-ups for observed sources has seen an FRB repeat, this could be because they have not observed for long enough. We discuss this further in section 3.

2.2 Young SNR Pulsars

About a dozen pulsars in our galaxy are known to emit extremely energetic, short duration radio pulses which can

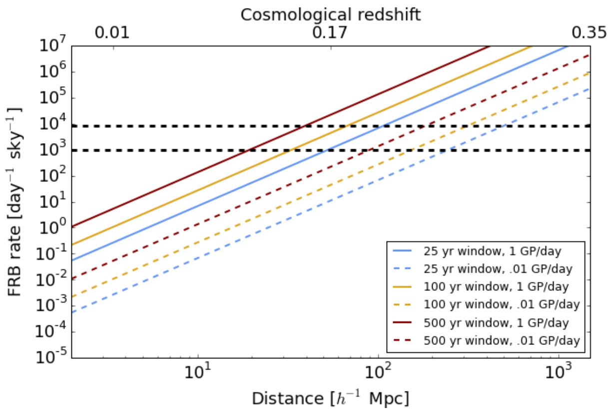

Figure 1. Daily FRB rate per sky based on local core-collapse supernova event rate, plotted against distance. We assume early in the pulsar's life there is a window, either 25, 100, or 500 years when the SNR can provide a large enough electron column density to explain the high DMs of the observed bursts. We also include a rate of giant pulses of either one per day or one per hundred days. We have assumed 20% of core-collapse supernovae leave behind a visible pulsar. The horizontal black lines are the 99% confidence bounds for the FRB rate found by Rane et al. (2015).

be many orders of magnitude brighter than the pulsar's regular emission. Some of these objects exhibit a rare tail of *supergiant* pulses, whose brightness temperatures exceed the Planck temperature, $\gtrsim 10^{32}$ K (Cordes et al. 2004). Indeed the largest known brightness temperature, T_b, in the universe came from a giant pulse from the Crab, with $T_b \sim 2 \times 10^{41}$ K (Taylor et al. 2014). Though there is only $\sim$ 100 hours of published giant pulse data from the Crab, it is known that the supergiant pulse tail does not obey the standard power-law fall off in amplitude (Mickaliger et al. 2012).

Given the relatively high frequency of core-collapse supernovae in the local universe, the young rapidly rotating pulsars such events leave behind could emit giant pulses bright enough to be observed at hundreds of megaparsecs. These supergiant pulses would require 10^{36-37} ergs of output, assuming and observed flux density of 0.3-5 Jy and $\sim$ 500 MHz of bandwidth over 1 ms. Though this is $\sim$ billions of times brighter than an average pulse, it is negligible compared to a pulsar's total rotational energy, $E_{rot} \sim 10^{49-50}$ ergs and even the pulsar's spin-down luminosity. We also point out that given its relative proximity, this model requires a couple orders of magnitude less energy than cosmological FRBs, located beyond a Gpc.

The polarization properties of giant pulses are also consistent with those of observed FRBs. Giant pulses are known to be highly polarized, switching between strong Stokes V and purely linearly polarized states. The only published FRB with full-pol information was FRB 140514 was found to have $\sim$ 20% circular polarization and no detectable linear polarization (Petroff 2014). We expect some FRBs to be linearly polarized, and potentially exhibit polarization angle swings over the burst duration.

3 PREDICTIONS

In table 1 we summarize the observational consequences of ours and several other models as best we can. As one might expect, the most striking differences in predictions has to do with the distance of FRBs, for example the cosmological FRB models differ mainly just in their expected counterpart.

The young SNR pulsar model makes several predictions that will be addressed with more data, particularly with full polarization observations and large field-of-view surveys. The latter will provide a large sample of FRBs whose flux and DM statistics can give us information about their location. Since in the SNR FRB picture most of the DM is intrinsic, the sources do not need to be at cosmological distances. This means the flux distribution is given by a Euclidean universe that is only weakly dependent on DM, $N(>S) \propto S^{-3/2}$, assuming the bursts are standard candle-like. Surveys like CHIME (Bandura 2014), UTMOST[2], or HIRAX could observe as many as $\sim 10^{3-4}$ per year, which would allow for detailed population statistics.

Since we have proposed that FRBs come from young pulsars in supernova remnants, it is possible that the corresponding supernova was observed in recent decades in the optical. If the pulsars were younger than $\sim$60 years old they could be localized with VLBI measurements and matched against catalogued type II supernovae.

We also point out that while FRBs seem not to repeat regularly, it is not known that they never repeat. Though the statistics of giant pulses from local pulsars are mostly Poisson (Sallmen et al. 1999), it is possible that the super-giant pulses we require from very young SNR pulsars are not. If their statistics were of a Poisson process then there are already limits on the repeat rate, given the $\sim$ 100 hours of follow up, however if their statistics were more like earthquakes, the brightest pulses could burst intermittently and turn off for extended periods. It is possible that FRBs could repeat every 5-500 days. If they were to repeat, it is possible that their DMs, RMs, and scattering properties could change noticeably on months/years timescales. Unlike standard pulsars whose RMs and DMs are constant to a couple decimal places, young SNR pulsars like the Crab and Vela have shown significant - and sometimes correlated - variation in such properties (Rankin et al. 1988; Kuzmin et al. 2008). We also predict that such repeated bursts could have vastly different polarization states, similar to the giant pulses from pulsars in our own galaxy. Depending on the relationship between the giant pulse rate and SNR age and environment, there may exist a short window in the pulsar's life when DMs are larger than could be achieved in the IGM at redshifts $z \lesssim 2.5$. Naïvely we would expect the average pulse energy to decay with time along with its period. It would be therefore possible, albeit rare, that an FRB have a dispersion measure of $\sim 10^4$ pc/cm^3. In general we expect the distribution of DMs to be peaked somewhere around the observed FRBs, but with weight at intermediate DMs when the ejecta has significantly expanded and at very high DMs.

Another interesting path for studying extragalactic radio bursts, cosmological or otherwise, is scintillation. Only objects of small angular size scintillate, which is why stars twinkle and planets do not: turbulent cells in the ionosphere

[2] http://www.caastro.org/news/2014-utmost

Location	Model	Galactic scintillation	Faraday rotation	$\frac{\mathrm{dlnN_{FRB}}}{\mathrm{dlnS_\nu}}$	Counterpart	DM range ($\mathrm{pc/cm^3}$)	Pol angle swing
Cosmological ($\gtrsim 1h^{-1}$Gpc)	Blitzars	×	$\lesssim 7$ rad/m^2	?	gravitational waves	300-2500	?
	Merging COs	×	$\lesssim 7$ rad/m^2	?	type Ia SNe, X-ray, γ-ray	300-2500	×
	Primordial BHs	×	$\lesssim 7$ rad/m^2	?	∼TeV	300-2500	×
	Magnetar flare	×	$\lesssim 7$ rad/m^2	?	∼ms TeV burst	300-2500	✓
Extragalactic, local ($\lesssim 200h^{-1}$Mpc)	Edge-on disk	✓	50-500 rad/m^2	-3/2	?	10-2000	?
	Nuclear magnetar	✓	10^{3-5} rad/m^2	-3/2	None	10-3000	✓
	SNR pulsar	✓	20-10^3 rad/m^2	-3/2	Archival CC SNe	10^2-10^4	✓
Galactic ($\lesssim$ 100 kpc)	Flaring MS stars	✓	RM$_{gal}$	-3/2	Main sequence star	$\gtrsim 300$	×
Terrestrial ($\lesssim 10^5$ km)	RFI	×	$\lesssim$ RM$_{ion}$	$\begin{cases}-1/2\ if\ 2D \\ -3/2\ if\ 3D\end{cases}$	None	?	×

Table 1. This table summarizes a number of FRB models by classifying them as cosmological, extragalactic but non-cosmological, Galactic, and terrestrial. The seven columns are potential observables of FRBs and each row gives their consequence for a given model (Blitzars (Falcke & Rezzolla 2014), compact object mergers (Mickaliger et al. 2012; Totani 2013), exploding primordial blackholes (Barrau et al. 2014), bursts from magnetars (Lyubarsky 2014), edge-on disk galaxies (Xu & Han 2015), circumnuclear magnetars (Pen & Connor 2015), supernova remnant pulsars, stellar flares (Loeb et al. 2014), and terrestrial RFI (Hippke et al. 2015).). Since scintillation only affects unresolved images, cosmological sources that are not scattered near the source will not scintillate in our galaxy, while non-cosmological sources whose screens are intrinsic will. For Faraday rotation and scintillation we assume the RM and SM comes from the same place as the DM, e.g. the IGM for cosmological sources, though such models could introduce a more local Faraday effect or a scattering screen. Even though all models have to explain the observed 500-1500 pc/cm^3, some models predict a wider range of DM. For instance, in the circumnuclear magnetar or edge-on disk disk scenarios there ought to be bursts at relatively low DM that simply have not been identified as FRBs. In our supernova remnant model DMs should be very large early in the pulsar's life, though this window is short and therefore such high DM bursts would be rare.

can resolve planets but not stars. The same is true for extragalactic objects scintillating in the Milky Way, where objects larger than $\sim 10^{-7}$ arc seconds do not scintillate at ∼GHz. This is why so few quasars scintillate (Dennett-Thorpe & de Bruyn 2002).

While several explanations for this scintillation exist (Narayan 1992; Pen & Levin 2014), we are concerned with the observational effects and not the physics. Using Thompson et al. (1986) FRBs we can estimate the angular size of an extragalactic object,

$$\theta \approx \left(\frac{2c\tau\,(R_{\rm obj} - R_{\rm sn})}{R_{\rm sn} R_{\rm obj}} \right)^{-1/2} \tag{5}$$

where R_{obj} is the distance to the source, R_{sn} is the distance to the screen, and τ is the scattering timescale. For FRBs we take τ to be $\sim$ 10 ms. In the cosmological case, if the ms scattering were from an extended galactic disk along the line of sight (see McQuinn (2014)) halfway between us and the source, then the angular broadening of an object at 2 Gpc is $\sim$ 150 microarcseconds. If the screen were within 1 kpc of the same object then the broadening is $\sim$ 80 nanoarcseconds. Therefore scintillation from our own galaxy should only occur for cosmological FRBs whose millisecond scattering is close to the source. For an SNR FRB the screen would have to be within a few hundred parsecs of the object, which we generically expect. We include this feature in table 1 where each column is estimated based on the medium that is causing the high dispersion measure, e.g. the IGM for cosmological models.

4 CONCLUSIONS

Evidence is emerging suggesting FRBs are not only extraterrestrial but extragalactic. Though the simplest interpretation of their high DMs is a cosmological one, we find this model less compelling in the light of scattering measurements and potential Faraday rotation (see footnote [1]) and in this letter we offer a more nearby solution. We have gone through a model in which fast radio bursts are really supergiant pulses from extragalactic supernova remnant pulsars, within a couple hundred megaparsecs. The SNR environment is sufficiently dense and ionized to provide DMs $\gtrsim$ 500pc/cm^3 as well as RMs $\gtrsim$ 50 rad/m^2, only the first of which could be replicated by the IGM.

The nebula could also provide ∼ms scattering at 1 GHz, as has been observed in Galactic SNR pulsars. That makes this picture self-contained in the sense that the young remnant environment can account for the dispersion and scattering measure seen in FRBs. It predicts a higher Faraday rotation than the IGM, but not as high as galactic centers. The repetition rate is related to the distance, and could be from days to years. By extrapolating Crab-like giant pulses back to the pulsar's first century or so, we have proposed that such objects can emit extremely energetic bursts sporadically. If these are similar to giant pulses from Galactic pulsars, they could be highly polarized, either linearly or circularly, and if they were to repeat their polarization state may change drastically. Given the object's rotating nature, polarization angles would be likely to swing during the pulse (we remind the reader of the previous disclosure).

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