

# Non-Cosmological FRB’s from Young Supernova Remnant Pulsars

Liam Connor<sup>1,2,3\*</sup> Jonathan Sievers<sup>4†</sup> Ue-Li Pen<sup>1,5,6‡</sup>

<sup>1</sup> *Canadian Institute for Theoretical Astrophysics, University of Toronto, M5S 3H8 Ontario, Canada*

<sup>2</sup> *Department of Astronomy and Astrophysics, University of Toronto, M5S 3H8 Ontario, Canada*

<sup>3</sup> *Dunlap Institute for Astronomy and Astrophysics, University of Toronto, Toronto, ON M5S 3H4, Canada*

<sup>4</sup> *Astrophysics and Cosmology Research Unit, University of KwaZulu-Natal, Durban, South Africa*

<sup>5</sup> *Canadian Institute for Advanced Research, Program in Cosmology and Gravitation*

<sup>6</sup> *Perimeter Institute for Theoretical Physics, 31 Caroline St. N., Waterloo, ON, N2L 2Y5, Canada*

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## ABSTRACT

We propose a new extragalactic but non-cosmological explanation for FRB’s based on very young pulsars in supernova remnants. Within a few hundred years of a core-collapse supernova the ejecta is confined within  $\sim 1$  pc, providing a high enough column density of free electrons for the observed  $500\text{--}1500$  pc/cm<sup>3</sup>. By extrapolating a Crab-like pulsar to its infancy in an environment like that of SN 1987A, we hypothesize such an object could emit supergiant pulses sporadically which would be bright enough to see at a few hundred megaparsecs. In this scenario Faraday rotation at the source gives RM’s 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 (FRB’s) 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 IGM. However their relative scarcity (only  $\sim$  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 DM’s ( $\sim 500\text{--}1200$  pc/cm<sup>3</sup>) far exceeding the expected contribution from our own galaxy’s ISM and leading to the interpretation that FRB’s 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 FRB’s 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 ( $\sim 10^4$  per day per sky) and high DM’s, explanations of FRB’s 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<sup>2</sup> (Oppermann et al. 2015). The observed temporal scattering is problematic for a IGM interpretation, 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 ex-

\* E-mail: connor@astro.utoronto.ca

† E-mail: jonathan.sievers@gmail.com

‡ E-mail: pen@cita.utoronto.ca

tragalactic 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<sup>3</sup> of dispersion if the pulses are observed within  $\sim 100$  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<sup>1</sup>. 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,

$$DM \approx \frac{x_e M_{ej}}{m_p \frac{4\pi}{3} v_{ej}^2 t^2} \quad (1)$$

where  $x_e$  is the ionization fraction,  $M_{ej}$  is the ejecta mass, and  $m_p$  is the mass of a proton. Assuming  $\sim 10 M_\odot$  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<sup>3</sup> immediately after the reverse-shock ionization, to several hundred pc/cm<sup>3</sup> after 50-100 years. A similar treatment by Zanardo et al. (2014) found that a possible pulsar in SNR 1987a could have DM's between 100-6000 pc/cm<sup>3</sup>, after  $\sim 25$  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<sup>2</sup>, 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<sup>2</sup> of RM Oppermann et al. (2015).

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

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

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,

$$RM \approx 0.81 \text{ rad/m}^2 \times \frac{\langle B_{\parallel} \rangle}{1\mu G} \cdot \frac{DM}{1\text{pc/cm}^3} \quad (3)$$

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 -  $1\mu G$ . For instance the Crab and Vela have  $\sim 0.92\mu G$  and  $\sim 0.56\mu G$ , respectively. This gives RM's between  $\sim 80 - 1200$  rad/m<sup>2</sup> for a SNR pulsar with FRB-like DM's.

### 2.1 Event Rates

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

$$\Gamma_{FRB} \sim \frac{4}{3} \pi d_{max}^3 \times \Gamma_{CC} \times \eta \tau_{ion} \gamma_{GP} \quad (4)$$

where  $\tau_{ion}$  is the window in years when the SNR is sufficiently dense and ionized to provide the observed DM's and  $\gamma_{GP}$  is the daily rate of giant pulses brighter than  $\sim 500$  mJy, and  $\eta$  is the number of core-collapse supernovae that leave behind a visible pulsar. From Taylor et al. (2014) we know  $\Gamma_{CC} \sim 3 \times 10^{-4} \text{ day}^{-1} (h^{-1}\text{Mpc})^{-3}$ , so if we take  $d_{max}$  to be 100  $h^{-1}\text{Mpc}$  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 figure 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.

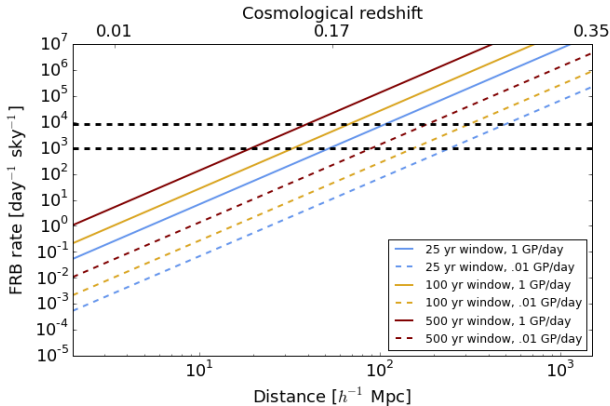
From this figure we can see even in our most conservative estimate, when the SNR only has a 25 year window and emits giant pulses once every 100 days, the volume necessary for the highest daily FRB rate is still non-cosmological. By this we mean the DM contribution from the IGM is less than  $\sim 200$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

If FRB's 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 be many orders of magnitude brighter than the pulsar's regular emission. Some of these objects exhibit a rare tail of *super-giant* pulses, whose brightness temperatures exceed the

<sup>1</sup> The authors disclose access to unpublished data prior to making these predictions



**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 DM's 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).

Planck temperature,  $\gtrsim 10^{32}$  K (Cordes et al. 2004). Indeed the largest known brightness temperature 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 an 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. We also point out that given its relative proximity, this model requires a couple orders of magnitude less energy than cosmological FRB's, located beyond a Gpc.

The polarization properties of giant pulses are also consistent with observed those of FRB's. 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 FRB's to be linearly polarized, and potentially exhibit polarization angle swings over the burst duration.

### 3 PREDICTIONS

In table 2.2 we try and 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 FRB's, for example the cosmological FRB models largely differ 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 FRB's 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,  $N(> S) \propto S^{-3/2}$ . Surveys like CHIME (Bandura 2014), UTMOST<sup>2</sup>, or HYRAX could observe as many as  $\sim 10^{3-4}$  per year, which would allow for detailed population statistics.

Since we have proposed that FRB's 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 FRB's 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 supergiant 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 FRB's could repeat every 5-500 days. If they were to repeat, it is possible that their DM's, RM's, and scattering properties could change noticeably on months/years timescales. Unlike standard pulsars whose RM's and DM's 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 DM's are larger than could be achieved in the IGM. It would be therefore possible, albeit rare, that an FRB have a dispersion measure of  $\sim 10^4$  pc/cm<sup>3</sup>.

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 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  $\sim$ GHz. This is why so few quasars scintillate (Dennett-Thorpe & de Bruyn 2002).

Using Thompson et al. (1986) we can estimate the angular size of an extragalactic object,

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

where  $R_{obj}$  is the distance to the source,  $R_{sn}$  is the distance

<sup>2</sup> <http://www.caastro.org/news/2014-utmost>

Location	Model	Galactic scintillation	Faraday rotation	$\frac{d \ln N_{\text{FRB}}}{d \ln S_\nu}$	Counterpart	DM range (pc/cm <sup>3</sup> )	Pol angle swing
Cosmological ( $\gtrsim 1h^{-1}\text{Gpc}$ )	Blitzars	No	$\lesssim 7 \text{ rad/m}^2$	?	gravitational waves	300-2500	?
	Merging COs	No	$\lesssim 7 \text{ rad/m}^2$	?	Type Ia SNe, X-ray, $\gamma$ -ray	300-2500	No
	Primordial BHs	No	$\lesssim 7 \text{ rad/m}^2$	$\leq -3/2$	$\sim \text{TeV}$	300-2500	No
	Magnetar flare	No	$\lesssim 7 \text{ rad/m}^2$	?	$\sim \text{ms TeV}$ burst	300-2500	✓
Extragalactic, local ( $\lesssim 200h^{-1}\text{Mpc}$ )	Edge-on disk	✓	50-500 rad/m <sup>2</sup>	-3/2	?	10-2000	?
	Nuclear magnetar	✓	$10^3\text{--}5 \text{ rad/m}^2$	-3/2	None	10-3000	✓
	SNR pulsar	✓	20-10 <sup>3</sup> rad/m <sup>2</sup>	-3/2	Archival CC SNe	10 <sup>2</sup> -10 <sup>4</sup>	✓
Galactic ( $\lesssim 100\text{kpc}$ )	Flaring MS stars	✓	-RM <sub>gal</sub>	-3/2	Main sequence star	$\gtrsim 300$	No
Terrestrial ( $\lesssim 10^4\text{km}$ )	RFI	No	-RM <sub>gal</sub>	$\begin{cases} -1/2 \text{ if } 2D \\ -3/2 \text{ if } 3D \end{cases}$	None	?	No

**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 FRB’s 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 presumably have already been scattered will not scintillate in our galaxy, while non-cosmological sources will. For Faraday rotation we assume the RM comes from the same place as the DM, e.g. the IGM for cosmological sources. Even though all models have to explain the observed 500-1500 pc/cm<sup>3</sup>, 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 FRB’s. In our supernova remnant model DM’s should be very large early in the pulsar’s life, though this window is short and therefore such high DM bursts would be rare.

to the screen, and  $\tau$  is the scattering timescale. For of FRB’s we take  $\tau$  to be  $\sim 10$  ms. In the cosmological case, if the 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 FRB’s 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 2.2 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 piling on suggesting FRB’s are not only extraterrestrial but extragalactic. Though the simplest interpretation of their high DM’s is a cosmological one, we find this model less compelling in the light of scattering measurements and potential Faraday rotation<sup>1</sup> 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 DM’s  $\gtrsim 500\text{pc/cm}^3$  as well as RM’s  $\gtrsim 50 \text{ rad/m}^2$ , only the first of which could be replicated by the IGM.

The nebula could also provide  $\sim \text{ms}$  scattering at 1 GHz, as has been observed in galactic supernova remnant

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 FRB’s. 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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