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Non-Cosmological FRB's from Young Supernova Remnant Pulsars

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ABSTRACT

We take into account recent polarization and scattering measurements of fast radio bursts and 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 ∼1 pc, providing a high enough column density of free electrons for the observed 300-1500 pc/cm^3. 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gives RM's much larger than the expected cosmological contribution, which may have been seen in a recently discovered unpublished burst. Therefore the scattering, large DM, and relatively high RM all come from one place in our model, which is not the case for the cosmological interpretation. Our 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 a great deal of 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 ∼ 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 (∼ 500-1200 pc/cm^3) 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 (Pfahl & Loeb 2004). 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 (∼10^4 per day per sky) and high DM's, explanations of FRB's must now account for temporal scattering, unusual polarization states, and perhaps Faraday rotation. If the latter is consistently found to be a larger effect than expected from cosmological Faraday rotation, then the $z_{FRB} \sim 1$ picture becomes somewhat paradoxical since it means the dispersion and Faraday rotation are not both due to the burst's large distance (Oppermann et al. 2015). The observed temporal scattering is also problematic, 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

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years of the core-collapse supernova. In our picture the large DM, the scattering, and the Faraday rotation all come from the same place, which is different from the cosmological interpretation. The giant pulses can also explain the observed polarization states of FRB's.

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 wave heating of the ejecta plasma. Though the shock-heated ejacta 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 (**?**) 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,

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

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 $v_{ej} \sim 3-8\times10^3$ 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 **?** found that a possible pulsar in SNR 1987a could have DM's between 100-6000 pc/cm^3, after $\sim$ 25 years.
Another potentially important feature of the SNR environment is its magnetic field. We have reason to believe at least some FRB's are Faraday rotated at the level of $\sim$ hundreds of rad/m^2, the exact magnitude of which 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).

The Faraday effect rotates the polarization vector by an angle ϕ =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,

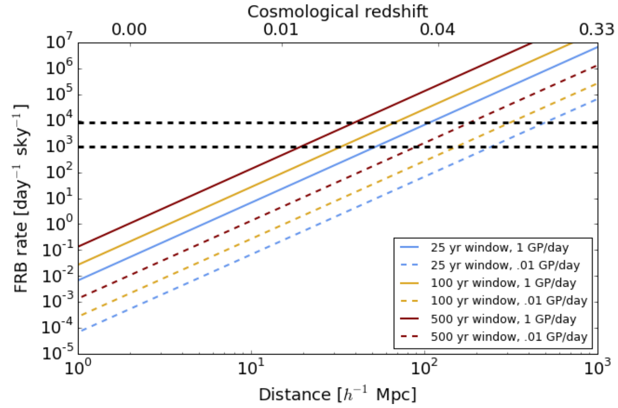

Figure 1. Daily FRB rate per sky based on local core-collapse supernova event rate, plotted against distance. We assume early in the pulsar's life there is a window, either 25, 100, or 500 years when the SNR can provide a large enough electron column density to explain the high DM's of the observed bursts. 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).

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

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 RM's between $\sim 80-1200$ rad/m^2 for a SNR pulsar with FRB-like DM's, and this is consistent with the observed Faraday rotated burst.

2.1 Event Rates

The daily FRB rate has been estimated at $3.3^{+5.0}_{-2.5}\times10^3$ 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,

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

where τ_{ion} is the window in years when the SNR is sufficiently dense and ionized to provide the observed DM's and γ_{GP} is the daily rate of giant pulses brighter than $\sim$ 500 mJy, and η is the number of core-collapse supernovae that leave behind a visible pulsar. From Taylor et al. (2014) we know $\Gamma_{CC} \sim 3\times10^{-4}$ day^{-1} (h^{-1} 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 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 ~ 200 pc/cm^3. If the SNR FRB's are within a hundred h^{-1} 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 *supergiant* pulses, whose brightness temperatures exceed the Planck temperature, $\gtrsim 10^{32}$ K (Cordes et al. 2004). Indeed the largest observed brightness temperature came from a giant pulse from the Crab , with T$_b \sim 2 \times 10^{41}$ (Taylor et al. 2014). Though there is only ~ 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). If an instrument with very little forward gain and no real-time RFI cut, like a single dipole, were to monitor the Crab from several $\sim$ months we would have a better idea of the statistics and frequency of such events.

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. 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).

3 PREDICTIONS

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 that 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 ($N(S) \propto S^{-5/2}$). Surveys like CHIME (Bandura 2014), UTMOST[1], 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 ~ 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.

Finally, 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^3.

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 and polarization measurements, 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 $\gtrsim 300$pc/cm^3 as well as RM's $\gtrsim 100$ rad/m^2, only the first of which could be replicated by the IGM.

The nebula could also provide $\sim$ms scattering at 1GHz, 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 - and perhaps Faraday rotation - seen in FRB's. 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

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

could be highly polarized, either linearly or circularly, and if they were to repeat their polarization state may change drastically.

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