



# What if the Fast Radio Bursts 110220 and 140514 Are from the Same Source?

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## Abstract

The fast radio bursts (FRBs) 110220 and 140514 were detected at telescope pointing locations within 9 arcmin of each other over three years apart, both within the same 14.4 arcmin beam of the Parkes radio telescope. Nevertheless, they generally have not been considered to be from the same source because of a vastly different dispersion measure (DM) for the two bursts by over  $380 \text{ pc cm}^{-3}$ . Here, we consider the hypothesis that these two FRBs are from the same neutron star embedded within a supernova remnant (SNR) that provides an evolving DM as the ejecta expands and becomes more diffuse. Using such a model and the observed DM change, it can be argued that the corresponding SN must have occurred within  $\approx 10.2$  years of FRB 110220. Furthermore, constraints can be placed on the SN ejecta mass and explosion energy, which appear to require a stripped-envelope (Type Ib/c) SN and/or a very energetic explosion. A third FRB from this location would be even more constraining, allowing the component of the DM due to the SNR to be separated from the unchanging DM components due to the host galaxy and intergalactic medium. In the future, if more FRBs are found to repeat, the sort of arguments presented here can be used to test the young neutron star progenitor hypothesis for FRBs.

**Key words:** pulsars: general – radio continuum: general – stars: magnetic field – stars: neutron

## 1. Introduction

Fast radio bursts (FRBs) are a recently discovered class of transients characterized by millisecond bursts of radio radiation (Lorimer et al. 2007; Keane et al. 2012; Thornton et al. 2013; Ravi et al. 2015). Due to their uncharacteristically high dispersion measures (DMs), they likely occur at cosmological distances and/or in extreme density environments (see discussions in Kulkarni et al. 2014; Luan & Goldreich 2014; Lyubarsky 2014; Katz 2016a and references therein). Furthermore, they appear to be very common, with an inferred rate of  $\sim 10^4$  FRBs on the sky per day (Rane et al. 2016). Nevertheless, there has been no astrophysical object or progenitor event definitively connected to FRBs, which has inspired a large number of theoretical studies to solve the mystery of identifying their progenitor. This includes magnetized neutron stars (NSs) collapsing to black holes (Falcke & Rezzolla 2014), asteroids and comets falling onto NSs (Geng & Huang 2015; Dai et al. 2016), radio flares related to soft gamma-ray repeaters (Lyutikov 2002; Popov & Postnov 2010; Kulkarni et al. 2014, 2015; Lyubarsky 2014; Katz 2016b), giants pulses from young pulsars (Cordes & Wasserman 2016; Connor et al. 2016; Lyutikov et al. 2016; Popov & Pshirkov 2016), circumnuclear magnetars (Pen & Connor 2015), flaring stars (Loeb et al. 2014), merging charged black holes (Liu et al. 2016; Zhang 2016), NS–white dwarf binaries (Gu et al. 2016), white dwarf mergers (Kashiyama et al. 2013), and magnetic NS mergers (Hansen & Lyutikov 2001; Piro 2012; Wang et al. 2016).

Some of the strongest constraints on FRB models come from the repeating FRB 121102 (Spitler et al. 2014, 2016; Scholz et al. 2016) because it is difficult to reconcile any of the cataclysmic scenarios mentioned above with continued repetition for  $>4$  years. This has focused many in the community on the two scenarios of either soft gamma-ray repeater-related progenitors or giant pulse analogs from young pulsars. Furthermore, the location of FRB 121102 has now been

measured (Chatterjee et al. 2017; Marcote et al. 2017). This allowed the host to be identified, which, surprisingly, was a galaxy with a low stellar mass of  $\sim (4\text{--}7) \times 10^7 M_\odot$ , reminiscent of the hosts of superluminous supernovae (SNe) and long gamma-ray bursts (Tendulkar et al. 2017). This is interesting because just like FRBs, magnetar-related scenarios have also often been invoked for these other types of extreme transients (Metzger et al. 2017). A persistent radio source has also been identified at the location of the FRB, which could be related to the forward shock of an energetic SN or an extreme pulsar wind nebula (Murase et al. 2016; Metzger et al. 2017; Kashiyama & Murase 2017).

This all begs the question though: how much of what we learn from FRB 121102 can we apply to other FRBs? Is FRB 121102 the only FRB that repeats, or do they all repeat? And if they do, why have we not found them yet? This has inspired efforts to follow up the locations of known FRBs to investigate whether they can be seen to repeat (e.g., Petroff et al. 2015b). Thus far, there has not definitely been another repeating FRB, but there was one event that was especially interesting. FRB 140514 (Petroff et al. 2015a) had a DM of  $562.7 \text{ pc cm}^{-3}$  and was found to be within 9 arcmin of a previous FRB 110220 (Thornton et al. 2013) with a DM of  $944.4 \text{ pc cm}^{-3}$ . Given the size of the Parkes error region ( $\gtrsim 14$  arcmin FWHM) these two FRBs can be considered potentially colocated. Petroff et al. (2015a) estimated the probability of a chance FRB at 32%, and so based on this non-negligible probability and the large difference in DM, they argued that FRB 140514 was probably a separate source. In contrast, Maoz et al. (2015) re-analyzed the probability of a chance FRB at this location based on the survey sky coverage and FRB rate. They found a probability of  $\sim 1\%$  and concluded that they likely had the same source. This work then argued that the different DMs between the two bursts ruled out a cosmological intergalactic medium (IGM) origin for the DM, but might be explained by a flare-star scenario with a varying plasma blanket between bursts (Loeb et al. 2014). However, could this DM

difference be explained by the evolution of dispersing material close to the source with the source at extragalactic distances?

Motivated by these interesting puzzles, here we study whether FRBs 110220 and 140514 could be from the same source and whether the changing DM could be due to the expansion of an SN remnant (SNR). Such a picture is naturally expected for the young NS scenario (Connor et al. 2016; Lyutikov et al. 2016; Piro 2016) as well as some magnetar scenarios if the magnetar is young (Metzger et al. 2017). In Section 2, we present a toy model for the SNR evolution and describe what constraints can be placed on it in comparison to FRBs 110220 and 140514. In Section 3, we apply many of the same arguments to the repeating FRB 121102. In Section 4, we summarize our main results and discuss potential implications that stem from our work.

## 2. Constraints from FRBs 110220 and 140514

### 2.1. Supernova Remnant Model

As an SNR expands and cools, the material initially recombines over the timescale of approximately months to about a year. Soon after though, the interaction of the SNR with the interstellar medium (ISM) creates a reverse shock that passes back through the ejecta. This shock reaches temperatures sufficient to ionize the material, producing free electrons that can now once again disperse radio emission (Piro 2016).

Assuming that the Milky Way component of an FRB's DM can be subtracted out, the remaining total observed DM is

$$\text{DM}_{\text{tot}}(t) = \frac{\text{DM}_{\text{SNR}}(t)}{1+z} + \frac{\text{DM}_{\text{host}}}{1+z} + \text{DM}_{\text{IGM}}, \quad (1)$$

where  $\text{DM}_{\text{SNR}}(t)$ ,  $\text{DM}_{\text{host}}$ , and  $\text{DM}_{\text{IGM}}$  are the components to the DM from the SNR, host galaxy, and IGM, respectively, and  $z$  is the redshift to the source. The IGM component is given by

$$\text{DM}_{\text{IGM}} = \frac{n_0 c}{H_0} z, \quad (2)$$

where  $H_0$  is Hubble's constant and  $n_0 = 1.6 \times 10^{-7} \text{ cm}^{-3}$  is the present-day density assuming the baryons are homogeneously distributed and ionized (Katz 2016c). At its most simplistic level, an SNR with mass  $M$  and expanding with a velocity  $v$  provides a time-dependent DM of

$$\begin{aligned} \text{DM}_{\text{SNR}}(t) &\approx \frac{3fM}{4\pi(vt)^2\mu_e m_p} \\ &= 9.4 \times 10^3 \mu_e^{-1} v_9^{-2} t_{\text{yr}}^{-2} f_{0.1} \left( \frac{M}{M_\odot} \right) \text{pc cm}^{-3}, \end{aligned} \quad (3)$$

where  $f$  is the fraction of the ejecta that has been ionized by the reverse shock (note that an energetic central source, such as a magnetar, could contribute to ionizing the ejecta from the inside-out; Metzger et al. 2017) with  $f_{0.1} = f/0.1$ ,  $m_p$  is the proton mass,  $\mu_e$  is the mean molecular weight per electron,  $v_9 = v/10^9 \text{ cm s}^{-1}$ , and  $t_{\text{yr}} = t/1 \text{ years}$ . For a pure hydrogen composition,  $\mu_e = 1$ , for a solar composition  $\mu_e \approx 1.2$  and for a heavier composition (as in a stripped-envelope SN)  $\mu_e \approx 2$ .

The unchanging contributions to the DM from the host and IGM make it difficult to tease out the SNR contribution. One way to overcome this is by considering the change in DM instead, since these constant factors will stay the same.

**Table 1**  
Comparison of FRBs 110220 and 140514

Name	FRB 110220 <sup>a</sup>	FRB 140514 <sup>b</sup>
Event date UTC	2011 Feb 20	2014 May 14
Event time UTC	01:55:48.96	17:14:11.06
R.A.	22 <sup>h</sup> 34 <sup>m</sup> 38 <sup>s</sup>	22 <sup>h</sup> 34 <sup>m</sup> 06 <sup>s</sup>
Decl.	−12°24′	−12°18′
DM <sub>FRB</sub> (pc cm <sup>−3</sup> )	944.4	562.7
DM <sub>MW</sub> (pc cm <sup>−3</sup> )	34.9	34.9
Observed width (ms)	5.6	2.8
Peak flux density (Jy)	1.3	0.47
Fluence (Jy ms)	8.0	1.3

**Notes.**

<sup>a</sup> Thornton et al. (2013).

<sup>b</sup> Petroff et al. (2015a).

Calculating the integral from times  $t_1$  to  $t_2$ , one finds

$$\Delta\text{DM}_{\text{tot}} = -\frac{3fM}{4\pi v^2 \mu_e m_p} \left( \frac{1}{t_1^2} - \frac{1}{t_2^2} \right) (1+z)^{-1}. \quad (4)$$

Taking  $t_1 = t$  and  $t_2 = t + \Delta t$ , in the limit that  $t \gg \Delta t$ , then

$$\begin{aligned} \Delta\text{DM}_{\text{tot}} &\approx -\frac{3fM}{2\pi(vt)^2 \mu_e m_p} \frac{\Delta t}{t} (1+z)^{-1} \\ &= -\frac{1.9 \times 10^4}{1+z} \mu_e^{-1} v_9^{-2} t_{\text{yr}}^{-2} \frac{\Delta t}{t} f_{0.1} \left( \frac{M}{M_\odot} \right) \text{pc cm}^{-3} \end{aligned} \quad (5)$$

can be used as an approximation for the change in DM.

For FRBs 110220 and 140514, the decrease in DM was  $381.7 \text{ pc cm}^{-3}$  on a timescale of  $\Delta t = 3.2 \text{ years}$ , as can be seen from Table 1 along with other properties of these FRBs. Using Equation (5) we can then estimate roughly when the SN associated with FRBs 110220 and 140514 occurred as a function of the mass of the ejecta, resulting in

$$t \approx 5.4(1+z)^{-1/3} \mu_e^{-2/3} v_9^{-2/3} f_{0.1}^{1/3} \left( \frac{M}{M_\odot} \right)^{1/3} \text{ years}. \quad (6)$$

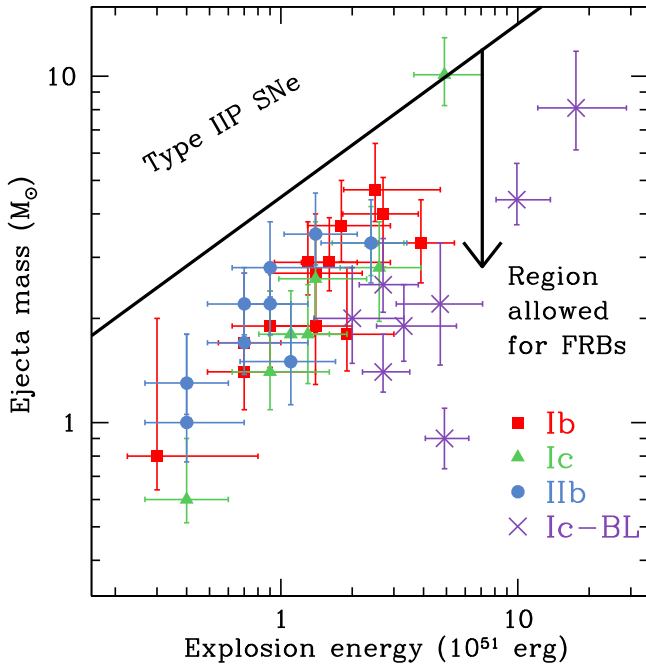
Thus, the SN must have occurred rather recently to explain the observed change in DM.

### 2.2. Constraints on Explosion Time, Ejecta Mass, and Supernova Properties

In fact, even more stringent, model-independent constraints on the explosion time can be made by considering the ratio of the DMs. This is given by

$$\begin{aligned} &\frac{\text{DM}_{\text{SNR}}}{(1+z)(t_{\text{yr}} + 3.2)^2} + \frac{\text{DM}_{\text{host}}}{1+z} + \text{DM}_{\text{IGM}} \\ &\frac{\text{DM}_{\text{SNR}}}{(1+z)t_{\text{yr}}^2} + \frac{\text{DM}_{\text{host}}}{1+z} + \text{DM}_{\text{IGM}} \\ &= \frac{527.8}{909.5} = 0.58, \end{aligned} \quad (7)$$

where we have subtracted out the Milky Way component from each DM, and on the left-hand side, we assume that  $\text{DM}_{\text{SNR}}$  is evaluated at 1 years after the SN. The thing to note is that the non-zero contributions of  $\text{DM}_{\text{host}}$  and  $\text{DM}_{\text{IGM}}$  always push the ratio closer to unity. Thus, independent of the details of the SN,



**Figure 1.** Stripped-envelope SN ejecta masses and explosion energies estimated by Lyman et al. (2016) for 38 different events. The colors and symbols denote Type Ib (events that show helium; red squares), Type Ic (events that show no helium; green triangles), Type IIb (events that show helium and trace hydrogen at early times; blue circles), and Type Ic-BL (events that show no helium and are especially energetic; purple crosses). The solid black line is the limit placed by Equation (10) using  $f = 0.1$ ,  $\mu_e = 2$ , and  $z \ll 1$ . The upper left corner marked “Type IIP SNe” labels the parameter regime roughly found for hydrogen-rich SNe by Pejcha & Prieto (2015). Note that when comparing to these events that  $\mu_e \approx 1.2$ , and thus the black lines should be moved down by a factor of  $\approx 1.3$ .

this ratio must obey the limit that

$$\frac{t_{\text{yr}}^2}{(t_{\text{yr}} + 3.2)^2} < 0.58 \Rightarrow t < 10.2 \text{ years.} \quad (8)$$

Thus, if these FRBs are associated with a young NS, the SN must have taken place less than 10.2 years before FRB 110220.

Given this more model-independent constraint on the explosion time, we can turn this around and put a constraint on the SN ejecta mass. Basically, if the SN happened so recently, the ejecta cannot be too massive. Otherwise, it would provide too large of a DM. Taking Equation (3), setting  $\text{DM}_{\text{SNR}} = 909.5(1+z) \text{ pc cm}^{-3}$ , and using the time limit given by Equation (8) results in

$$M < 10.1(1+z)f_{0.1}^{-1}\mu_e v_9^2 M_{\odot}. \quad (9)$$

This can also be related to the energy of the explosion using  $E \approx Mv^2/2$  resulting in

$$M < 2.2(1+z)f_{0.1}^{-1/2}\mu_e^{1/2}E_{51}^{1/2} M_{\odot}, \quad (10)$$

where  $E_{51} = E/10^{51} \text{ erg}$ .

We write the mass constraint in this way because it helps in comparing to SN observations. In particular, Lyman et al. (2016) use the light curves of 38 stripped-envelope SNe (explosions that have had all or most of their hydrogen stripped) to estimate the ejecta masses and explosion energies. This is summarized in Figure 1 with the various colors and symbols designating the various subclasses of events. In comparison, we show the constraint placed by Equation (10),

where we take  $f = 0.1$  (only a small amount of ionization given the early stages inferred by the time limit) and  $\mu_e = 2$  (appropriate for SNe of these types). This comparison shows that these stripped-envelope SNe naturally have the ejecta masses and energetics consistent with this limit.

In contrast, we also label the region that roughly corresponds to hydrogen-rich SNe as “Type IIP SNe” in the upper left corner (using the work of Pejcha & Prieto 2015). This shows that a hydrogen-rich SN just has too much mass around to explain the DM for these FRBs (as found in the more detailed discussion by Piro 2016). In particular, note that hydrogen-rich material has more electrons per unit mass than the hydrogen-deficient material of a stripped SN; thus, for  $\mu_e \approx 1.2$  the solid line in Figure 1 should move down by a factor of  $\approx 1.3$ .

A natural question to ask is whether a connection can be made between the SN constraints made here and the unique galaxy host found for the repeating FRB 121102. For a stellar mass of  $\sim (4-7) \times 10^7 M_{\odot}$  (Tendulkar et al. 2017) and the normal mass–metallicity relation (Tremonti et al. 2004), one would expect the host to have a very sub-solar metallicity (although the currently available limits only constrain it to be solar metallicity or below). In contrast, SNe Ib and Ic happen preferentially in hosts with larger metallicities than Type II (e.g., Prieto et al. 2008). The Type Ic-BL that do not have associated gamma-ray bursts also follow regions with a similarly high metallicity (e.g., Modjaz et al. 2008, 2011). The main events that have a preference for low-metallicity environments are hydrogen-deficient superluminous SNe and long gamma-ray burst (e.g., Perley et al. 2016a, 2016b), as has been pointed out by Metzger et al. (2017). Such events would have parameters that roughly follow the Type Ic-BL points in Figure 1, and thus be consistent with the limits we find here.

Another possibility is that the connection between the host galaxy and the FRB is not the presence of a magnetar but rather a quickly spinning progenitor. The low metallicity environments are commonly thought to inhibit mass and angular momentum loss, allowing a massive star to spin much more quickly near the end of its life as needed for generating engine-driven explosions (e.g., Yoon & Langer 2005). In fact, Piro (2016) argues that it is preferential to have NSs born with a fast spin ( $\lesssim 3 \text{ ms}$ ), but a relatively normal magnetic field ( $\lesssim 10^{12} \text{ G}$ ) if FRBs are powered by the NS rotation. This is because a high magnetic field would cause the NS to spin down too quickly when the SN remnant is still too optically thick. In this picture, long gamma-ray bursts and superluminous SNe may represent the most extreme cases where a dynamo is able to generate an especially large field, while FRBs are from progenitors with lower fields. Nevertheless, in each case the connection to the low-metallicity host is a high spin. This might also help explain the high rate of FRBs, since both long gamma-ray bursts and superluminous SNe occur at rates too small by orders of magnitude in comparison to FRBs.

### 2.3. Absorption, Dispersion, and Scattering Constraints

There are other important constraints to consider for an SNR to be able to explain the changing DM between FRBs 110220 and 140514. The first is that the radio emission should not be inhibited by free-free absorption (Kulkarni et al. 2015; Piro 2016; Murase et al. 2017). For radiation at frequencies  $h\nu \ll k_B T$ , where  $T$  is the temperature, the absorption



coefficient is (Rybicki & Lightman 1979)

$$\alpha_{\text{ff}} = 1.9 \times 10^{-2} T^{-3/2} Z^2 n_e n_i \nu^{-2} g_{\text{ff}} \text{ cm}^{-1}, \quad (11)$$

where  $Z$  is the average charge per ion;  $n_e$  and  $n_i$  are the electron and ion number densities, respectively;  $g_{\text{ff}} \sim 1$  is the Gaunt factor; and all quantities are in cgs units. Estimating  $n_e = 3fM/4\pi(vt)^3\mu_e m_p$  and  $n_i = 3fM/4\pi(vt)^3\mu_i m_p$ , where  $\mu_i$  is the mean molecular weight per ion, and assuming the characteristic size to be  $vt$  results in a limit on the mass for  $t < 10.2$  years of

$$M < 20.6(1+z)T_4^{3/4}v_9^{5/2}\frac{(\mu_e\mu_i)^{1/2}}{f_{0.1}Z}\nu_{1.4}M_\odot, \quad (12)$$

where  $T_4 = T/10^4$  K and  $\nu_{1.4} = \nu/1.4$  GHz. Note the redshift factor of  $1+z$  is needed since  $\nu$  is the observed frequency and what matters for the absorption is the frequency in the frame of the source. Since  $Z \sim 5$  for hydrogen-deficient ejecta, again this constraint appears to argue for a lower mass like a stripped-envelope SN rather than a massive hydrogen-rich SN. This estimate is what is needed for the FRB to be observed at 1.4 GHz. At lower frequencies, the FRB may be absorbed. For example, if the mass marginally obeys the limit placed by Equation (9), then one would expect the FRB to be absorbed for frequencies

$$\nu < 680(1+z)^{-1}ZT_4^{-3/4}v_9^{-1/2}\left(\frac{\mu_e}{\mu_i}\right)^{1/2} \text{ MHz}. \quad (13)$$

This is more difficult to obey if  $Z$  is too large, which may argue that the masses must be below the limit of Equation (9). Interestingly, even though there have been searches for FRBs by the Low-Frequency Array, the Murchison Widefield Array, and the Green Bank Telescope at low frequencies, an FRB has never been seen below 700 MHz. Could this be explained by the presence of an SNR?

Another constraint is that the observed dispersion for these FRBs is very close to  $\nu \propto t^{-\alpha}$  with  $\alpha \approx 2$ . At high densities, the  $\alpha$  can be slightly higher than 2 (Katz 2016a):

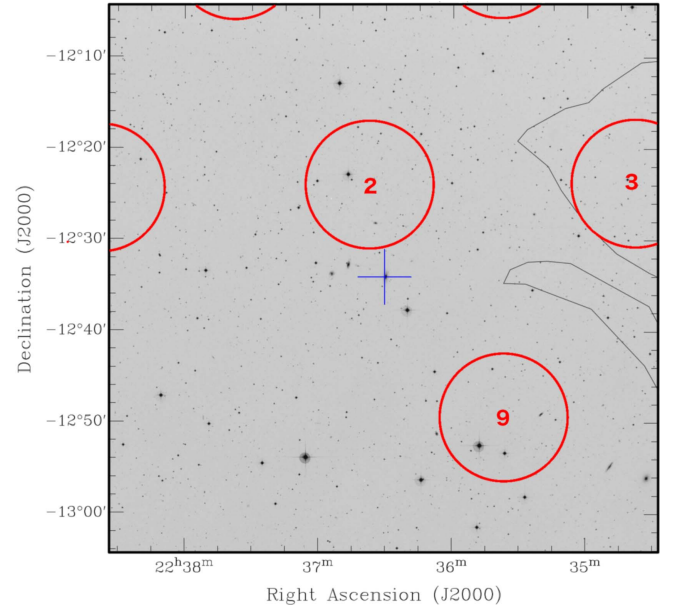
$$\alpha = 2 + \frac{3e^2 n_e}{2\pi m_e \nu^2}. \quad (14)$$

For the mass limit we find, this additional factor is  $\sim 10^{-6}$ , and thus we do not expect the SNR to have a strong impact on the time dependence of the dispersion.

The typical pulse width of FRBs is  $\sim 5$  ms, too broad to be explained by Kolmogorov turbulence in the IGM (Luan & Goldreich 2014). Furthermore, galactic pulsars show that scattering in the ISM cannot contribute significantly to the pulse widths of FRBs (Krishnakumar et al. 2015). The dense environment of an SNR might provide the necessary scattering. The delay attributed to scattering by an angle  $\Delta\theta$  is (Williamson 1972; Kulkarni et al. 2014; Katz 2016c)

$$W \approx \frac{vt}{2c}(\Delta\theta)^2. \quad (15)$$

For a timescale of  $t \sim 10$  years, this would require a scattering of  $\Delta\theta \sim 10^{-5}$ . As more FRBs are found and constraints made on the time since an associated SN, a better census on the scattering angles can be made.



**Figure 2.** Position of SN 2001hh (shown with a blue cross) in comparison to the Parkes beams at the time of the detection of the brighter FRB 110220 (beam positions and names shown with red circles). The bright beam 3 detection, coupled with the non-detection of the burst in adjacent beams 1, 2, 4, 9, and 10, places limits on the position of the burst (50% confidence limit shown as black bounds). If the FRB source was SN 2001hh, we would have expected to detect the FRB most significantly in beam 2 rather than beam 3.

#### 2.4. Where Is the Supernova?

The constraints that can be placed on the explosion time of an SN related to FRBs 110220 and 140514 naturally beg the question, where is the SN? In fact, looking through the SN archives we found that SN 2001hh took place in 2001 (Hakobyan et al. 2008), roughly on the same part of the sky as FRBs 110220 and 140514 and with a host galaxy redshift of  $z \sim 0.02$ , which is consistent with the DM-inferred upper redshift limit of FRB 140514 of  $z \lesssim 0.5$  (Petroff et al. 2015a). A detailed comparison of the locations is shown in Figure 2, which demonstrates that in fact SN 2001hh is roughly 38 arcmin away from the pointing location of FRB 110220. The location of the SN during the FRB 110220 detection indicates that if this SN and the FRB events were related, that FRB 110220 would have been detected in beam 2 rather than beam 3, as it was. Thus, the location and timing of SN 2001hh is an odd coincidence, but does not appear associated with these FRBs. Furthermore, SN 2001hh was Type II and may have had too much mass associated with it to explain the observed DM anyway.

The fact that an SN was not found associated with FRBs 110220 and 140514 does not rule out this model. In 2001, our ability to find all nearby SNe was much less than it is now, and it is quite reasonable that this SN was not found. This example does show that going into the future, we should be able to compare the locations of FRBs with nearby SNe to test whether the young NS scenario makes sense for these events.<sup>4</sup>

### 3. The Repeating FRB 121102

Similar arguments as presented above can also be applied to the repeating FRB 121102. In this case, the DM is not seen to

<sup>4</sup> For example, see <https://sne.space/frbs/> (Guillochon et al. 2017).

change with time, so we can only place limits. Using the fact that this FRB has been observed for  $\approx 4$  years and the DM is observed to be the same within  $\approx 3 \text{ pc cm}^{-3}$ , we can use Equation (5) to constrain the explosion time to be

$$t \gtrsim 30 v_9^{-2/3} (1+z)^{-1/3} f_{0.1}^{1/3} \left( \frac{M}{M_\odot} \right)^{1/3} \left( \frac{\Delta t}{4 \text{ years}} \right)^{1/3} \text{ years.} \quad (16)$$

Furthermore, since this FRB's distance is known, subtracting off the Milky Way and IGM contributions to the DM gives the rough limit that  $\text{DM}_{\text{SNR}} \lesssim 225(1+z) \text{ pc cm}^{-3}$  (Tendulkar et al. 2017). Using Equation (3), the ejecta mass must then satisfy

$$M \lesssim 21(1+z) f_{0.1}^{-1} v_9^2 \left( \frac{t}{30 \text{ years}} \right)^2 M_\odot. \quad (17)$$

Thus, we find that the repeating FRB 121102 is not inconsistent with a young NS origin as long as the SN occurred sufficiently long ago. The mass constraints we find are not too dissimilar from an SN, but are not as constraining as what was found for FRBs 110220 and 140514. As we continue to observe bursts from FRB 121102 and measure the associated DMs, we will be able to place tighter constraints on any potential SNR around this FRB.

Our inference that the repeater must be an older NS than the source that produced FRBs 110220 and 140514 may seem at odds with the fact that the repeater appears to be more active. This comes from the intuition that perhaps a younger NS would produce more FRBs. Note though that in the absence of a physical model for producing the FRBs, we do not know if this should be the case. For example, one could just as well imagine that when an NS is young it produces less frequent but more powerful FRBs, and as it ages and sputters down it may produce more frequent but less powerful FRBs as seen for the repeater. Until there is an agreed upon FRB model, we hesitate against using the properties of the actual bursts to infer anything about the age of the sources.

#### 4. Discussion and Conclusions

We have considered the hypothesis that FRBs 110220 and 140514 are from the same source with the difference in DM between the two bursts (of greater than  $380 \text{ pc cm}^{-3}$ ) due to the expansion of an SNR. From this, we can place constraints that the corresponding SN must have occurred  $< 10.2$  years before FRBs 110220 and that the ejecta mass of the SN must be relatively low or the SN must be very energetic, similar to what is measured for stripped-envelope SNe. We in fact found an SN at a similar time and location on the sky (SN 2001hh), but its distance of  $\sim 38$  arcmin from the nominal location of FRB 110220 means that the SN is probably not related. The observation of a third FRB from this location would be even more constraining, since this would allow the IGM and host components of the DM to be separated from the SNR component. With a reasonable estimate for the host component, the DM from the IGM would allow the distance to these FRBs to be estimated to hopefully narrow down which galaxies could potentially be the host of these FRBs.

Whether or not it ends up being true that FRBs 110220 and 140514 are from the same source, this work highlights the

various constraints that can be placed in the future as hopefully more FRBs are seen to repeat. Even in the case of FRB 121102, which has been seen to repeat but a change in the DM has not been observed, we have shown that interesting constraints can be placed on the young NS hypothesis for FRBs.

Looking ahead, there are a few key implications for future observations that stem from this work.

First, the potential for a time-dependent change in dispersion may impact searches for repeating FRBs. Searches that rely on multiple events appearing at one DM (say, to look for excesses at a given DM over observations at a month to year spacings, or follow-up searches that rely on coherent dedispersion to raise sensitivity to a fixed DM) will not uncover repeating events associated with the youngest SNe, for which rapidly changing DMs can occur.

Second, finding a low-frequency cutoff due to free-free absorption, as discussed in Section 2.3, would be important for probing the environment around FRBs. This cutoff should move to lower frequencies as the DM decreases. In the future, the Canadian Hydrogen Intensity Mapping Experiment (Bandura et al. 2014) will be ideally suited to do this since it will collect a large number of FRBs and be sensitive to a frequency range of 400–800 MHz where this free-free absorption is expected to occur. This result further highlights the fact that very low frequency observations ( $\lesssim 500$  MHz) will only probe a much older, and potentially less energetic, population of spinning compact objects.

Finally, as more FRBs are found, their locations should be compared with nearby SNe to test whether the young NS scenario makes sense for these events. This will be aided by surveys with rapid cadences that will increase our efficiency for discovering SNe, such as the All-sky Automated Survey for Supernovae (ASAS-SN; Shappee et al. 2014) and the Zwicky Transient Facility (ZTF; Law et al. 2009), as well as the Large Synoptic Survey Telescope (LSST; LSST Science Collaboration et al. 2009), which will provide a comprehensive record of almost every SN at larger distances. FRBs with especially high DMs might be important in this sense if their large DMs indicate they are being found soon after the explosion.

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