Cosmological Fast Radio Bursts from Binary White Dwarf Mergers

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Fast Radio Bursts

Parks 64m “High Transient Radio Universe” survey
High latitude (-70 deg < b < -30 deg)

Thornton+13

\[ \nu \sim 1.4 \text{ GHz} \]

\[ S_\nu \sim 0.4-1.3 \text{ Jy} \]

\[ \Delta t < 5 \text{ ms} \]
Fast Radio Bursts

Parks 64m “High Transient Radio Universe” survey
High latitude (-70 deg < b < -30 deg)

Thornton+13

\[ \nu^{-2} \] arrival time pulse sweep

Only detected in a single beam
Radio Dispersion

Dispersion relation in ionized media

\[ \omega^2 = k^2 c^2 + \omega_{pe}^2 \quad \omega_{pe} = \sqrt{\frac{4\pi n_e e^2}{m_e}} \]

arrival time:

\[ T = \int^L \left( \frac{\partial \omega}{\partial k} \right)^{-1} ds \sim \frac{L}{c} + \frac{2e^2}{m_e c \nu^2} \int^L n_e ds \]

\[ \equiv DM \]

\[ \Delta T \sim 4.2 \text{ s} \left( \frac{\nu}{\text{GHz}} \right)^{-2} \left( \frac{DM}{10^3 \text{ cm}^{-3} \text{ pc}} \right) \]
Galactic Dispersion

Fig. S2. Measured DM for FRBs and known pulsars is plotted against the magnitude of Galactic latitude. The FRBs from this paper are shown as blue triangles, FRB 010621 and 010724 are shown as black squares, pulsars are indicated by red '+' symbols. The FRBs exhibit significantly higher dispersion than pulsars at similar separations from the Galactic plane. The pulsars with an apparent dispersion excess located at $30^\circ < |b| < 45^\circ$ are in the Magellanic clouds which provide an additional source of free electrons and dispersion.

Thornton+13

Einstein symposium@Harverd

14/10/29
Intergalactic Dispersion

\[\Delta t = \int_0^z dz \frac{dt}{dz} \frac{1}{2} \left(1 + \frac{v_e^2}{2}\right)\]

\[DM_{IGM} = n_e,0 \frac{c}{H_0} \times \int_0^z (1 + z)dz \]

\[\int_0^z \left[\Omega_m (1 + z)^3 + \Omega_\Lambda\right]^{1/2}\]

(including missing baryons)

\[DM \sim 10^3 \text{ cm}^{-3} \text{ pc} \]

\[@z \sim 1\]
Lower limits on the distances

No direct feature from the ionized region
⇒ constraints on the size \((L)\) and the distance \((d)\)

The sources are extragalactic, or
The dispersions are intrinsic. c.f. “Perytons”

Kulkani+14
If cosmological …
Event rate

Thornton+13

• Observing 4078 deg$^2$ (0.098 sky) for 270 s
  $\Rightarrow R_{\text{FRB}}(F \sim 3 \text{ Jy ms}) \sim 10^4 \text{ sky}^{-1} \text{ day}^{-1}$

• Lorimer burst (FRB 010724)
  $\Rightarrow R(F \sim 150 \text{ Jy ms}) = 225 \text{ sky}^{-1} \text{ day}^{-1}$
  consistent with $N \propto F^{-3/2}$

• $R_{\text{FRB}} \sim 10^{-3} \text{ yr}^{-1} \text{ gal}^{-1}$
  c.f. $R_{\text{CCSN}} \sim 10^{-2} \text{ yr}^{-1} \text{ gal}^{-1}$
  $R_{\text{NS-NS}} \sim R_{\text{GRB}} \sim 10^{-5} \text{ yr}^{-1} \text{ gal}^{-1}$
**Brightness Temperature**

\[
T_B \sim 6 \times 10^{33} \text{ K} \\
\times S_{Jy} \nu_{\text{GHz}}^{-2} \delta t_{ms}^{-2} \Gamma^{-3} d_L^{2} \text{Gpc}
\]

coherent emission

unless \( \Gamma > 10^7 \)
Cosmological FRBs

- $DM = 500-1000 \, cm^{-3} \, pc \rightarrow z = 0.5-1$, $d_L \sim 2-6 \, Gpc$
- $\Delta t < 5 \, ms \rightarrow c \Delta t < 1500 (1+z)^{-1} \, km$
- $S_\nu \sim Jy \rightarrow E_{iso} \sim 10^{38-40} \, erg$
- $\sim 10^4 \, day^{-1} \, sky^{-1} \rightarrow \sim 10^{-3} \, yr^{-1} \, gal^{-1} \sim 0.1 \times R_{CCSN}$
- Coherent emission
- No repeated burst so far
- No counterpart so far
2. Possible Origins
Possible Origins

• Galactic
  – Rotating radio transients
  – Flaring stars

• Extragalactic
  – Giant pulse from young pulsars
  – Magnetar giant flares
  – Supernovae into nearby stars
  – Core-collapses of hypermassive NSs
  – Binary NS mergers
  – Binary WD mergers
  – Evaporations of BHs
  – Superconducting cosmic strings
Binary White Dwarf Mergers?

If the merged object rotates differentially, the magnetic fields are amplified up to the possible transient maximum magnetic-field strength. The total magnetic-field energy outside the polar cap is also a plausible site for fast radio bursts. Interestingly, numerical simulations show that the magnetic fields may be amplified by magnetorotational instabilities (Külbi et al. 2013; Ji et al. 2013). Hereafter, the pre-factor energy is enough for the total emitted energy in typical transient magnetic dissipation events in localized regions on magnetized astrophysical objects (Thompson & Duncan 1995). For example, soft gamma-ray repeater or magnetar flares would be rapid transient magnetic dissipation events (as in our case, the spin-down luminosity of the magnetized WD, which may trigger a short gamma-ray burst). The magnetic energy dissipation in the polar cap provides the right energy budget for a FRB. We consider a FRB as the mass-shedding limit, $r_{\text{emi}}$, of the new-born white dwarf pulsar.

We note that the spin-down luminosity of the newborn NSs, $L_{\text{sp-down}}$, can be as high as $\frac{4\pi f B_{\text{cap}}^2 r_{\text{cap}}}{c}$, using the average value $B_{\text{cap}} \approx 10^{12}$ Gauss, $r_{\text{cap}} \approx 10^{11}$ cm, and the angular frequency can be estimated as $\approx \frac{v}{r_{\text{cap}}}$, where $v$ is the transverse speed of the emitting shell.

In the polar cap region above the polar-cap region, the magnetic energy dissipation takes place ($r_{\text{cap}} \approx 10^{11}$ cm). The total magnetic-field energy outside the polar cap ($r_{\text{cap}}$) is given by $\frac{\pi \gamma^2 c}{2}$, where $\gamma$ is the Lorentz factor of the emitting shell. Hence, binary WD mergers may be one of the most promising sources of FRBs.
Energetics

WD-WD merger \(\rightarrow\) differential rotation \(\rightarrow\) B amplification

\[ E_{\text{max}} \approx \frac{GM^2}{R} \]
\[ \approx 10^{50} \text{ erg} \ M_0^2 R_{8.7}^{-1} \]

\[ \Omega \approx \frac{\nu}{r} \sim 1 \text{ s}^{-1} \ r_{8.7}^{-3/2} \]

\[ B_{\text{max}} \gtrsim 10^{11} \text{ G} \]

\[ E_B \approx \frac{B^2}{8\pi} \times \frac{4\pi r^3}{3} \sim 2 \times 10^{43} \text{ erg} \ B_9^2 r_{8.7}^3 \]

\text{c.f.} \ B_{\text{obs, max}} \sim 10^9 \text{ G} 

Kawka+07; Kepler+13
WD-WD merger $\rightarrow$ differential rotation $\rightarrow$ B amplification $\rightarrow$ B dissipation in the polar cap $\rightarrow$ injection of e$^\pm$ bunches

\[
\frac{r_{\text{cap}}}{c} \sim 2.3 \text{ ms } r_{8.7}^{3/2} \Omega_0^{1/2}
\]

\[
r_{\text{cap}} \approx r \left( \frac{r \Omega}{c} \right)^{1/2} \sim 6.7 \times 10^7 \text{ cm } r_{8.7}^{3/2} \Omega_0^{1/2}
\]
Event Rate

Radial velocity distribution of ~ 4000 WDs in SDSS → separation distribution ($\alpha$) & binary fraction ($f_{\text{bin}}$)

| $\alpha$      | $f_{\text{bin}}$ | Total Rate ($10^{-13}$ mergers yr$^{-1} M_\odot^{-1}$) | Super-Chandrasekhar Rate ($10^{-13}$ mergers yr$^{-1} M_\odot^{-1}$) |
|---------------|-----------------|-----------------------------------------------------|-----------------------------------------------------|
| Entire range  | 0.014–0.32      | 1.4 (0.16, 7.2)                                     | 0.1 (0.016, 0.4)                                   |
| 1.0           | 0.11–0.24       | 0.3 (0.065, 0.5)                                    | 0.03 (0.017, 0.045)                                |
| 0.0           | 0.046–0.22      | 1.0 (0.46, 2.2)                                     | 0.08 (0.03, 0.16)                                  |
| −1.0          | 0.021–0.11      | 3.0 (1.0, 6.0)                                      | 0.16 (0.05, 0.3)                                   |

$R_{WD-WD} \sim 10^{-2} - 10^{-3}$ yr$^{-1}$ gal$^{-1}$
Relativistic $e^\pm$ Bunch Formation

An huge E field along with the open B field

$$\Phi_{max} \approx \frac{B\Omega^2 r^3}{2c^2} \sim 2.5 \times 10^{16} \text{ Volt } B_9 \Omega_0^2 r_8^3$$

$e^\pm$ pair avalanche + acceleration

KK,Ioka,Kawanaka 11
Curvature Radiation

WD-WD merger $\rightarrow$ differential rotation $\rightarrow$ B amplification $\rightarrow$ B dissipation in the polar cap $\rightarrow$ injection of $e^{\pm}$ bunches $\rightarrow$ Coherent curvature radiation

\[ r_{emi} \approx r_c \lesssim r_{lc} \]
\[ \approx 3 \times 10^{10} \text{ cm} \ r_{8.7}^{3/2} \]

\[ \nu_c \approx \gamma^3 \frac{3c}{4\pi r_c} \]
\[ \approx 0.72 \text{ GHz} \ \gamma_3^{3} r_{c,10}^{-1} \]

\[ \gamma \geq 1100 \ \nu_9^{1/3} r_{c,10}^{1/3} \]
Luminosity

\[ L_{\text{tot}} \approx (P_c N_{\text{coh}}^2) \times N_{\text{pat}} \]

\[ P_c \approx \frac{2\gamma e^2 c}{3r_c^2} \sim 5 \times 10^{-17} \text{erg s}^{-1} \gamma_3^{-1} r_{c,10}^{-2} \]

\[ N_{\text{coh}} \approx n_e \times V_{\text{coh}} \approx n_e \times \frac{4}{\gamma^2} r_{\text{emi}}^2 \frac{c}{\nu_c} \sim n_e \times 2 \times 10^{16} \text{cm}^3 \gamma_3^{-5} r_{c,10} r_{\text{emi},10}^2 \]

\[ N_{\text{pat}} \approx \frac{V_{\text{emi}}}{V_{\text{coh}}} \approx \frac{4\pi f r_{\text{emi}}^2 r_{\text{cap}}}{V_{\text{coh}}} \sim 9 \times 10^{28} \text{cm}^3 f r_{\text{emi},10} r_{\text{cap},7.8}^2 \]

\[ L_{\text{tot}} \sim 4 \times 10^{42} \text{erg s}^{-1} f n_e,7 \gamma_3^{-1} r_{c,10}^{-1} r_{\text{emi},10}^4 r_{\text{cap},7.8} \]
Electron density

✓ Luminosity condition

\[ n_e \sim 2 \times 10^7 \text{ cm}^{-3} \ L_{43}^{1/2} \ \gamma_3^{1/2} \ r_{c,10}^{1/2} r_{emi,10}^{-2} r_{cap,7.8}^{-1/2} \]

✓ Plasma cutoff limit

\[ \nu_c \geq \nu_{pe} \approx \frac{\gamma}{2\pi} \left( \frac{4\pi n_e^' e^2}{m_e} \right)^{1/2}, \quad n_e^' = \frac{n_e}{\gamma} \]

\[ n_e \leq 0.6 \times 10^7 \text{ cm}^{-3} \ \gamma_3^{5} r_{c,10}^{-2} \]

✓ Required multiplicity

\[ \kappa_{GJ} = \frac{n_e}{n_{GJ}} = \frac{n_e}{B_{emi,10} \Omega / 2\pi ce} \sim 8 \times 10^3 \ n_e,7 B_{emi,5}^{-1} \Omega_0^{-1} \]

Comparable to young NS pulsars
Binary WD Merger Scenario

- Energetics
- Timescale
- Event rate
- Emission mechanism

Coherent curvature emission with

\[ \gamma \sim 10^{3-4} \text{ and } \kappa_{GJ} \lesssim 10^4 \]
Counterparts

- Supernova Ia (double degenerate model)
- X-ray debris disk
  - \( L_x < 10^{47} \) erg/s for \( \sim 100 \) s \( \rightarrow \) Swift for nearby FRBs
- Magnetically powered optical transient

Columns

| Time (s) | Process | Observation |
|---------|---------|-------------|
| 0.5     | Ejecta  |             |
| 6.64    | Ejecta  |             |
| 12.7    | Ejecta  |             |
| 32.1    | Ejecta  |             |
| 43.8    | Ejecta  |             |
| 56.0    | Ejecta  |             |
| 80.0    | Ejecta  |             |
| 104     | Ejecta  |             |
| 152.0   | Ejecta  |             |

\( L_x \) and \( L_{\gamma} \) are displayed in Table 1196 P. Lorén-Aguilar et al.: High resolution SPH simulations of white dwarf mergers
Summary

• Fast Radio Bursts
  – If cosmological
    high event rate $\sim 10^4 \text{ yr}^{-1} \text{ gal}^{-1}$ coherent bursts
  – Possible scenarios
    magnetar giant flares, binary white dwarf mergers, etc

• Perytons

• Multi-messenger observations
  – lower frequency radio
  – counterpart search

• FRB cosmology
Appendix
2. Future Observations
Detecting highly-dispersed bursts with next-generation radio telescopes

Figure 2. Expected number of FRBs per hour for various observatories in the high-scattering simulations. The coloured bars show the number of FRBs detectable in imaging surveys, assuming different spectral indices of: 0.0 (white), -1.0, -2.0, -3.0 and -4.0 (darkest grey). The number of FRBs detectable in beamformed surveys are indicated by the bars with a solid black outline. The DM range used was $0 - 6000$ pc cm$^{-3}$.

Figure 3. As Figure 2, but for the no-scattering simulations.

sensitivity to extragalactic sources is achieved when observing away from the Galactic plane ($|b| \gtrsim 10^\circ$), where the electron density along the line-of-sight, and therefore the scatter-broadening time, is lowest. This will impact all radio transient surveys, but is particularly important at low frequencies. Figure 4 shows the number of FRBs expected to be observed per hour using the LOFAR HBAs (black lines) and ASKAP (grey lines) in our high-scattering simulations as a function of the Galactic DM along the line-of-sight (see Table 3 for the specifications of the telescopes used in the simulations).
FRB Cosmology

\[ DM_{IGM} = \frac{3}{8\pi} \frac{cH_0\Omega_b}{Gm_p} \int_0^z \frac{(1 + z)dz}{[\Omega_m(1 + z)^3 + \Omega_\Lambda]^{1/2}} \]

\[ d_L = \frac{c(1 + z)}{H_0} \int_0^z \frac{dz}{[\Omega_m(1 + z)^3 + \Omega_\Lambda]^{1/2}} \]

- Reionization
- Missing baryon
- Dark energy, cosmological parameters, etc

McQuinn 13; Deng & Zhang 14; Kalkarni+14
Multi-messenger observations

• Lower frequencies with larger FOV
• Optical, X-ray, and gamma-ray counterparts?
• GW and neutrino counterparts?
Lorimer Burst, Sparker, FRB 010724

\[ \nu \sim 1.4 \text{ GHz} \]

\[ S_{\nu} \sim 30 \text{ Jy} \]
\[ \Delta t \sim 5 \text{ ms} \]

\( \equiv \nu^{-2} \text{ arrival time pulse sweep} \)
Lorimer Burst, Sparker, FRB 010724

$DM \sim 375 \text{ cm}^{-3}\text{pc}$

$DM_{MW} \sim 25 \text{ cm}^{-3}\text{pc}$

$DM_{SMC} \sim 50 \text{ cm}^{-3}\text{pc}$
Keane Burst, FRB 010621

- The Parkes Multi-beam Pulsar Survey
- 288 MHz band centered on ~1.4 GHz
- Detected in a single beam
- 13:02:10.795 UTC
- S/N ~ 16.3
- DM = 746±1 cm⁻³
- Peak flux ~ 0.4 Jy
- Pulse width ~ 7.8 ms
- No counterpart
- No repeated bursts
“Perytons”

- Hit all 13 receivers
- Temporal distributions (UTC range 0-3)
- Some show $\sim \nu^{-2}$ dispersion (some not)

The Astrophysical Journal, 727:18(5 pp), 2011

January 20

Burke-Spolaor et al.

Figure 1. Spectrograms and time series for several detections. (b)–(d) Data from the 13 beams have been summed to enhance the signal. Frequency channels with known interference have been blanked. (a) De-dispersed time series showing Peryton 08 in the 13 beam multibeam receiver as the beams are distributed on the sky. The widest separation of the pointing centers of the displayed beams is 1.7 deg. (b) De-dispersed time series and spectrogram of Peryton 08. The black lines trace the best-fit dispersive delay for this detection. (c) and (d) Spectrograms of Peryton 06 and 15, respectively.

3. NEW DISCOVERIES AND THEIR PROPERTIES

Our search revealed 16 pulses with two striking features that distinguish them from all others in the data: an apparent $\delta t \propto \nu^{-2}$ delay of a magnitude implying an extragalactic origin in the telescope’s pointing direction, and a simultaneous occurrence in all 13 telescope receivers at relative intensities of less than a factor of four (Figure 1). When a dispersive delay is fit to each detection, the values cluster about a net band delay $\Delta t = 360$ ms, indicating a close connection with the LB at $\Delta t = 355$ ms (Figure 2). The LB’s reported sky position was below the horizon for several detections, therefore the pulses could not have come from the same extragalactic source. Below, we give evidence that the 16 signals have a terrestrial origin.

The 29′ separation between each receiver’s beam position and >20 dB attenuation beyond 30′ from each beam center render it impossible for an on-axis, pointlike signal to appear in more than three beams at similar intensity (Staveley-Smith et al. 1996; Hunt & Wright 1992). Our detections were therefore made through a sidelobe of the Parkes antenna, and based on the consistency of signals in the beams, in each case the emitter was positioned $\gg 5$ deg from the telescope’s pointing direction.
FRBs ≠ Perytons?

- FRBs are detected in a single beam.
- Perytons have $\Delta t \sim 30-50$ ms, which is $\sim 10$ times larger than FRBs.
- Perytons have symmetric, but some FRBs have an exponential tail.
- Perytons have DM $\sim 200-400$ cm$^{-3}$pc, which is smaller than 4 FRBs.
- Atmospheric emissions at different heights?
  - Perytons $< 10$ km $< \text{Lorimer burst} < \text{FRBs}$

Kulkani+14
Arecibo Detects FRB 121102

Pulsar ALFA survey targeting low latitude (|b| < 5 deg)  Spitler+14

$\nu \sim 1.4 \text{ GHz}$

Hit a single beam (maybe a sidelobe)

$\Delta t \sim 3 \text{ ms}$

$DM \sim 557 \text{ cm}^{-3}$

$l \sim 180^\circ$

$> 3 \times D_M W$
Coherent radio emissions with GRBs?

**Figure 2.** DM vs. time for the two GRBs with single-pulse candidates. Single-pulse detections with a significance ≥ 6σ appear as circles in this plot, with the size proportional to the S/N. The detections are color coded according to their classification by the friends-of-friends algorithm as candidates (blue), false positives (red) and RFI (grey). Top panel: GRB 100704A with a single pulse candidate 1076 seconds after the GRB at a DM of 195 pc cm$^{-3}$, with a significance of 6.2σ and width of 6 ms. Bottom panel: GRB 101011A with a single pulse candidate 524 seconds after the GRB at a DM of 570 pc cm$^{-3}$, with a significance of 6.6σ and width of 25 ms. The time origin of these plots is the time that the telescope first arrived on source ($T_{\text{on}}$). For clarity, DMs from 1000 pc cm$^{-3}$ are not shown.
Host Galaxy

• Galactic center: DM > 700 cm$^{-3}$ pc
  – $W \propto \frac{D_{\text{obs}} D_{\text{scr}}}{(D_{\text{obs}} + D_{\text{scr}})^2}$
  – If $D_{\text{scr}} \ll D_{\text{obs}}$, it locates at the galactic center

• Elliptical host: low DW

• Spiral host: DM > 700 cm$^{-3}$ pc
  if $l > 87$ deg (5%)

• Intervening galaxy: $P < 5%$
Coherent emission

- Emission from $N$ particles

$$P_{tot} = \left| \sum_{k=1}^{N} E_k e^{i\phi_k} \right|^2$$

$$= \sum_{k=1}^{N} |E_k|^2 + \sum_{k \neq j} E_k E_j e^{-i(\phi_k - \phi_j)}$$

$$= PN + P \sum_{k \neq j} e^{-i(\phi_k - \phi_j)}$$

$$n^{-1/3} > \lambda \quad \rightarrow \quad P_{tot} = PN \quad \text{incoherent}$$

$$n^{-1/3} < \lambda \quad \rightarrow \quad P_{tot} = PN^2 \quad \text{coherent}$$
Compton scattering is enhanced by coherent photons

\[
\frac{\partial n(\nu, \Omega)}{\partial t} + c(\Omega \cdot \nabla)n(\nu, \Omega) = \frac{3\sigma_T}{8\pi} N \frac{h}{m_e c} n(\nu, \Omega)
\times \int (e \cdot e_1)^2 (1 - \Omega \cdot \Omega_1) \frac{\partial \nu^2 n(\nu, \Omega)}{\partial \nu} d\Omega_1,
\]

✓ induced Compton limit

\[
\gamma \geq 2000 r_c^{3/14} r_{emi,10}^{3/14} n_e,7^{3/14}
\]
Free-Free Absorption

\[ \tau_{ff} \sim 5 \Rightarrow 1.2-1.5 \text{ GHz can be strongly affected.} \]

✓ Hot ionized nebula

\[ \tau_{ff} \sim 2.7 \left( \frac{DM}{325 \text{ cm}^{-3} \text{ pc}} \right) \left( \frac{\nu}{1.4 \text{ GHz}} \right)^{2.1} \left( \frac{T_e}{8000 \text{ K}} \right)^{-1.35} \left( \frac{l}{0.01 \text{ pc}} \right)^{-1} \]

✓ Stellar wind

\[ \tau_{ff} \sim 1.9 \left( \frac{\dot{M}}{10^{-5} M_\odot \text{ yr}^{-1}} \right)^2 \left( \frac{v_w}{10^8 \text{ cm s}^{-1}} \right)^{-2} \left( \frac{l}{10^{15} \text{ cm}} \right)^{-3} \]
Coherent dedispersion is the more delay to the raw voltage data directly and completely. In beamformed analysis, this delay can be addressed everywhere DM is the dispersion measure in units of pc cm$^{-3}$.

We summarise the two propagation effects of dispersion and scattering on the bursts and de-erased theoretically and observed for Galactic sources (see Table 1). FRBs have DM values in excess of the maximum expected from Bhat et al. 2004, see Table 1). The scatter-broadening time of a pulsed signal passing through the ISM is related to the DM by the empirical law.

The frequency-dependent refractive index of a cold, ionised medium (ISM) and the intergalactic medium (IGM). How-er, once the correct DM of a source is known, it can be removed. Dispersion also provides a good way to correct theoretically and observed for Galactic sources (see Table 1). In this paper, we follow the convention of defining the spectral index as:

\[
\Delta t_{\text{DM}} = \frac{\text{DM}}{2.410 \times 10^{-4} \nu^2}
\]

\[
\log \tau_s = 2.12 + 0.154 \log(\text{DM}) + 1.07(\log \text{DM})^2 - 3.86 \log \nu
\]

\[
S_\nu = \frac{F}{14/10^{1/2} \tau_0 + \tau_s^2}
\]

\[
l_{\nu} \propto \tau_s^{-1} \propto \nu^{3.86}
\]
The FRBs discussed in Thornton et al. (2013). The other FRBs, with DMs of 944, 723, and 553 cm$^{-3}$ pc have scattering timescale upper limits of 1 ms. Figure 1. Scattering time at 1 GHz versus dispersion measure showing the radio pulsars (adapted from Bhat et al. 2004) along with current scattering constraints on FRBs. The green and blue triangles indicate the scattering timescale upper limits of 1 ms at 1.4 GHz for the FRBs discussed in Lorimer et al. (2007) and Keane et al. (2012), scaled to 1 GHz. The red circle indicates the scattering timescale of 1 ms scaled to 1 GHz measured for one of the FRBs discussed in Thornton et al. (2013). The other FRBs, with DMs of 944, 723, and 553 cm$^{-3}$ pc have scattering timescale upper limits of 1 ms.

Lorimer+13
Low (frequency) is More (Events)?

“The scattering effects at lower radio frequency are less than previously thought.”

Even \( z > 0.5 \) events can be detectable in surveys below 1 GHz

Sources may already be present in 350-MHz surveys with the GBT. Surveys at 150 MHz with 30 deg\(^2\) FoV could detect 1 event/hr above 30 Jy...
LOFAR non-detection

Stay tuned…

Coenen+14

@~140 MHz
ducing its peak flux. This means that decreasing frequency and scattering broadens the pulse, re

cosmological constants derived from the latest radial distance using that the observed emission has been cosmologically red-

Note, the value DM∞ comes from our Galaxy as i g n i fi c a n t c o n t r i b u t i o n t o t h e D M e x t r a g a l a c t i c b u r s t s sight rather than the luminosity and distance to the source.

(3.2) Simulations

transients will appear to drop more quickly with distance effects and binning time because the optimal signal-to-noise ratio (SNR) of a given

Table 1. Observed properties of known extragalactic bursts.

|                          | FRB 010724 | FRB 010621 | FRB 110220 | FRB 110627 | FRB 110703 | FRB 120127 |
|--------------------------|------------|------------|------------|------------|------------|------------|
| Observed Width (ms)      | 4.6        | 8.3        | 5.6        | < 1.4      | < 4.3      | < 1.1      |
| (τ₀² + τₛ²)¹⁄₂ (ms)      | 3.1        | 4.8        | 5.5        | < 1.1      | < 4.1      | < 0.9      |
| Predicted τₛ (ms)*       | 2.89       | 177        | 802        | 145        | 2251       | 28         |
| Dispersion Measure(pc cm⁻³) | 375±1     | 746±1      | 944.38±0.05| 723.0±0.3  | 1103.6±0.7 | 553.3±0.3  |
| Extragalactic DM (pc cm⁻³) | 330       | 213        | 910        | 677        | 1072       | 521        |
| Peak Flux Density (Jy)   | 30±10      | 0.4±0.1    | 1.3        | 0.4        | 0.5        | 0.5        |
| Spectral Index†²         | −4 ± 1     | 0±1        | 0±1        | 0±1        | 0±1        | 0±1        |
| Observed Rate (hr⁻¹ deg⁻²)‡ | 0.0019⁺⁻0.0045 | 0.00051⁺⁻0.0001 | 0.0017⁺⁻0.0013 | 0.0017⁺⁻0.0005 | 0.0017⁺⁻0.0005 | 0.0017⁺⁻0.0005 |

*From Bhat et al. (2004).
†Spectral index of the peak flux density.
‡Uncertainties are determined following Gehrels (1986).
imaging surveys, which may improve in the future.

Given here are calculated for the centre of the observing band. Imaging surveys are often much more expensive than the a priori. Both imaging surveys and beamformed observations are competitive. In the high-scattering simulations, beamformed observations are typically more effective in telescopes which are very sensitive (e.g., SKA-mid), imaging surveys are indicated by the bars with a solid black outline. These results are also tabulated in Appendix A.

Figures 2 and 3 show the results of the simulations for the high-scattering and no-scattering simulations respectively. In these plots, the number of FRBs detectable in beamformed observations is divided by the number of FRBs detectable in imaging surveys, assuming different spectral indices of: 0.0 (white), -1.0, -2.0, -3.0 and -4.0 (dark-grey). The number of FRBs detectable in imaging surveys is listed. For LOFAR, we use noise levels derived from current transient imaging surveys, which may improve in the future.

| Telescope         | $A_{\text{eff}}/T_{\text{sys}}$ (m²/K) | $\nu_{\text{low}}$ (MHz) | $\nu_{\text{high}}$ (MHz) | FoV (deg²) | Reference                                      |
|-------------------|--------------------------------------|---------------------------|---------------------------|------------|-----------------------------------------------|
| SKA-low           | 5000                                 | 50                        | 350                       | 27         | Dewdney et al. (2013)                         |
| SKA₁-low          | 1000                                 | 50                        | 350                       | 27         | Dewdney et al. (2013)                         |
| SKA-mid           | 10000                                | 1000                      | 2000                      | 0.5        | Dewdney et al. (2013)                         |
| SKA₁-mid          | 1630                                 | 1000                      | 2000                      | 0.5        | Dewdney et al. (2013)                         |
| LOFAR-HBA         | 110                                  | 155                       | 165                       | 150        | Stappers et al. (2011), van Haarlem et al. (2013) |
| LOFAR-LBA         | 0.5                                  | 30                        | 80                        | 100        | Stappers et al. (2011), van Haarlem et al. (2013) |
| MWA               | 13.0                                 | 185                       | 215                       | 375        | Tingay et al. (2013)                          |
| ASKAP             | 81                                   | 700                       | 1000                      | 30         | Johnston, Feain & Gupta (2009)                |
| MeerKAT           | 220                                  | 580                       | 1750                      | 1.0        | de Blok et al. (2010)                         |
| Parkes Multi-beam | 92                                   | 1230                      | 1518                      | 1.1        | Manchester et al. (2001)                      |
| Molonglo          | 277                                  | 790                       | 890                       | 12         | Green et al. (2012)                           |
| UTR-2             | 0.5                                  | 10                        | 20                        | 40         | Abranin et al. (2001)                         |
| LWA               | 30                                   | 50                        | 70                        | 20         | Ellingson et al. (2009)                       |

Table 3. Comparison of the parameters used for simulations of current and planned telescopes. The values of field-of-view and $A_{\text{eff}}/T_{\text{sys}}$ given here are calculated for the centre of the observing band listed. For LOFAR, we use noise levels derived from current transient imaging surveys, which may improve in the future.
Energy Injection

The spin-down luminosity is not enough.

\[ L_{sd} \approx \frac{B^2 r^6 \Omega^4}{c^3} \sim 1.7 \times 10^{38} \text{ erg s}^{-1} \]

\[ B_9 r_{8.7}^6 \Omega_0^4 \ll 10^{43} \text{ erg s}^{-1} \]

\[ \text{cf. solar flares} \]

\[ \text{magnetar flares} \]

\[ \text{Magnetic energy dissipation in the polar cap} \]

\[ \text{Newly born white dwarf pulsar} \]
Magnetized White Dwarfs

Mt. Stromlo Observatory
H-rich DA WD
Zeeman splitting

Kawka+07

![Cumulative distributions of magnetic white dwarfs](image)

Table: Statistics of Magnetism in Local White Dwarfs

| Field Strength (kG) | Number of Magnetic WDs | Number of Nonmagnetic WDs | Fraction |
|---------------------|------------------------|---------------------------|----------|
| < 1                 | 1                      | 12                        | 0.08     |
| 1-10                | 1                      | 13                        | 0.08     |
| 10-100              | 1                      | 15                        | 0.08     |
| 100-1000            | 1                      | 18                        | 0.08     |
| 1000-10000          | 1                      | 21                        | 0.08     |
| 10000-100000        | 1                      | 24                        | 0.08     |
| 100000-1000000      | 1                      | 27                        | 0.08     |
| > 1000000           | 1                      | 30                        | 0.08     |

Figure 10: Cumulative distribution of magnetic white dwarfs within 13 pc and 20 pc.