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On the detectability of extragalactic fast radio transients

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ABSTRACT

Recent discoveries of highly dispersed millisecond radio bursts by Thornton et al. in a survey with the Parkes radio telescope at 1.4 GHz point towards an emerging population of sources at cosmological distances whose origin is currently unclear. Here, we demonstrate that the scattering effects at lower radio frequencies are less than previously thought, and that the bursts could be detectable at redshifts out to about $z = 0.5$ in surveys below 1 GHz. Using a source model in which the bursts are standard candles with bolometric luminosities $\sim 8 \times 10^{44}$ ergs s^{-1} uniformly distributed per unit comoving volume, we derive an expression for the observed peak flux density as a function of redshift and use this, together with the rate estimates found by Thornton et al. to find an empirical relationship between event rate and redshift probed by a given survey. The non-detection of any such events in Arecibo 1.4 GHz survey data by Deneva et al., and the Allen Telescope Array survey by Siemion et al. is consistent with our model. Ongoing surveys in the 1–2 GHz band should result in further discoveries. At lower frequencies, assuming a typical radio spectral index $\alpha = -1.4$, the predicted peak flux densities are 10 s of Jy. As a result, surveys of such a population with current facilities would not necessarily be sensitivity limited and could be carried out with small arrays to maximize the sky coverage. We predict that sources may already be present in 350 MHz surveys with the Green Bank Telescope. Surveys at 150 MHz with 30 deg^2 fields of view could detect one source per hour above 30 Jy.

Key words: scattering – intergalactic medium – cosmology: theory.

1 INTRODUCTION

In the last few years, a small population of sources emitting short-duration (‘fast’) transient radio bursts has been found. The bursts are bright, last no more than a few milliseconds, are broad-band and show the characteristic signature of dispersion by a cold plasma medium. Dispersion results in a frequency-dependent arrival time across the band, proportional to the integral of the electron column density along the line of sight, otherwise known as the DM (DM). The prototypical fast radio burst (FRB) was discovered by Lorimer et al. (2007) at a DM of 375 cm^{-3} pc in archival pulsar survey data of the Magellanic clouds (Manchester et al. 2006). In a reanalysis of Parkes Multibeam Pulsar Survey data, Keane et al. (2011, 2012) identified an FRB with a DM of 746 cm^{-3} pc. Recently, Thornton et al. (2013) report the discovery of four further FRBs at DMs in the range 550–1100 cm^{-3} pc. Given detailed models of the Galactic electron column density distribution, these high DMs place these sources far beyond the extent of the Galaxy and signify the emergence of a population of cosmological transients with exciting applications as probes of new physics and the intergalactic ionized medium.

Dispersion is not the only frequency-dependent effect incurred from propagation through an ionized plasma. FRBs will also be scattered due to inhomogeneities in this medium, with scattered rays arriving at the telescope later than those travelling on the direct line of sight (e.g. Rickett 1990). The resulting observed scattered pulse can be well approximated in most cases by a Gaussian pulse convolved with an exponential tail, with temporal constant $\tau_{\rm sc}$ scaling with frequency ν as $\tau_{\rm sc} \propto \nu^{\eta}$. Although it was often assumed that $\eta = -4.4$, as expected for Kolmogorov turbulence (Rickett 1990), Löhmer et al. (2001) found a flatter dependence where $\eta = -3.4 \pm 0.1$. Later, from a larger sample of pulsars, Bhat et al. (2004) found that $\eta = -3.9 \pm 0.2$ and presented an empirical relation between $\tau_{\rm sc}$ and DM (see Section 2). These two quantities correlate well for the Galactic population of pulsars, albeit with a dispersion of up to an order of magnitude on either side of the DM-$\tau_{\rm sc}$ curve.

Using the results of surveys at 1400 MHz, we investigate event rate predictions for surveys at 150 and 350 MHz. The 150 MHz band

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is pertinent given the advent of the Low Frequency Array (LOFAR; Stappers et al. 2011) as a wide field of view low-frequency transient monitor. The 350 MHz band is covered by all-sky pulsar surveys being carried out at the Green Bank Telescope (GBT; Boyles et al. 2013; Lynch et al. 2013; Rosen et al. 2013) and at Arecibo (Deneva et al. 2013). In Section 2, we demonstrate that the scattering in low-frequency surveys is less severe if FRBs are at cosmological distances. In Section 3, we describe a simple model that provides testable event rate predictions for ongoing and future surveys. We discuss these results in Section 4 and present our conclusions in Section 5.

2 ANOMALOUS SCATTERING IN EXTRAGALACTIC FAST TRANSIENTS

Lorimer et al. (2007) discussed the possibility of detecting FRBs with low-frequency telescopes. The burst they detected showed evolution of pulse width with frequency, but they could not determine whether this was intrinsic or due to scattering. The ∼ms scattering expected at a DM of 375 $\mathrm{cm^{-3}}$ pc at 1 GHz scales to a scattering time-scale of the order of 1 s at 150 MHz, leading to their suggestion that the pulse would be undetectable at those frequencies. However, of the six FRBs known so far, only one (FRB 110220) has had a measurable scattering time-scale at 1.4 GHz. The observation that the FRBs all lie significantly below the bulk of pulsars in the Bhat et al. (2004) DM-τ_{sc} curve, suggests that, for a particular DM, there is less scattering for an extragalactic source than would be expected from interpreting the curve.

For FRBs of extragalactic origin, the total scattering is made up of two contributions: interstellar scattering in the host galaxy and our own Galaxy, and intergalactic scattering caused by the intervening intergalactic medium. Despite the fact that most of the scattering material is found in the interstellar medium of the host or our Galaxy, geometrical considerations (e.g. Williamson 1972) suggest that contributions to scattering from media near the source or near the observer are expected to be small. To estimate the impact of this, we rewrite equation 2 from McClure-Griffiths et al. (1998) in terms of the scattering induced by a screen at a fractional distance *f* along the line of sight. As $f \to 0$, the screen is close the observer, and as $f \to 1$, the screen is close to the source. In this case the scattering time

$$\tau_{sc} = 4\tau_{max}(1 - f)f, \qquad (1)$$

where τ_{max} is the maximum scattering induced for a screen placed mid-way along the line of sight ($f = 0.5$). For scattering originating from a host galaxy at cosmological distances, $(1 - f)$ is the size of the host galaxy divided by the distance to the source, i.e. $(1 - f) \simeq 50\,\mathrm{kpc}/500\,\mathrm{Mpc} = 10^{-4}$ for a Galaxy with the extent of the Milky Way at the distance inferred for the Lorimer et al. (2007) FRB. Therefore, the scattering effects of our own Galaxy or the host galaxy can be essentially neglected for bursts at cosmological distances.

The same geometric considerations suggest that the most efficient scattering along the line of sight towards FRBs of extragalactic origin will occur in the medium near the mid-way point. Measurements of the scattering measure (SM) along extragalactic lines of sight[1] by Lazio et al. (2008) suggest values that are typically $\lesssim 10^{-4}$

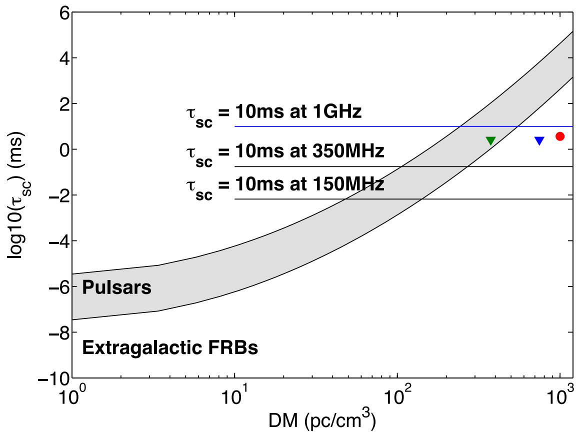

Figure 1. Scattering time at 1 GHz versus DM showing the radio pulsars (adapted from Bhat et al. 2004) along with current scattering constraints on FRBs. The triangles indicate the scattering time-scale upper limits of 1 ms at 1.4 GHz for the FRBs discussed in Lorimer et al. (2007) and Keane et al. (2012), scaled to 1 GHz. The circle indicates the scattering time-scale 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 $\mathrm{cm^{-3}}$ pc have scattering time-scale upper limits of 1 ms.

SM of Galactic lines of sight, despite the large distances to extragalactic sources. Given that $\tau_{sc} \propto \mathrm{sM}^{6/5}$ and the distance (Cordes & Lazio 2002), similar pulse broadening times could be observed for a Galactic source at 5 kpc as for an extragalactic source at ≈300 Mpc. In Fig. 1, we show our adaptation of the DM-τ_{sc} curve and plot the FRB scattering time-scales scaled to an observing frequency of 1 GHz. Here, we see that the upper limit on the scattering time-scale for the FRB of Keane et al. (2012) lies well below the expected trend for Galactic pulsars, as does the time-scale for the one event of four for which Thornton et al. (2013) were able to measure τ_{sc}. Taking the 1 ms of scattering at 1.4 GHz of this event, which scales to 3.66 ms at 1 GHz, and comparing it to the predicted value of $10^{3.63}$ ms, suggests that rescaling the Bhat et al. (2004) equation:

$$\log \tau_{sc} \simeq -6.5 + 0.15(\log \mathrm{DM}) + 1.1(\log \mathrm{DM})^2 - 3.9 \log f, \qquad (2)$$

so that the leading term is −9.5 rather than −6.5 provides an estimate of the expected scattering for extragalactic sources. In this expression, DM takes its usual units of $\mathrm{cm^{-3}}$ pc and the frequency, *f*, is in GHz. Note that, given that only one measurement of the scattering time-scale has been made so far, it is likely that this is an upper limit to the average amount of scattering as a function of DM.

In summary, based on the theoretical expectations of low scattering towards FRBs of extragalactic origin and the recent 1.4 GHz observations in which little or no scattering is observed, FRB scattering at frequencies below 1 GHz is also expected to be substantially less than would be the case if they were of Galactic origin. This raises the possibility that they can be detectable in surveys at lower frequencies. In the remainder of this Letter, we discuss the implications of this conclusion and make predictions using a population model.

3 EVENT RATE PREDICTIONS FOR FAST TRANSIENT SURVEYS

The events reported by Thornton et al. (2013), along with those previously (Lorimer et al. 2007; Keane et al. 2012) imply a substantial population of transients detectable by ongoing and planned radio

[1] SM is the line integral of the electron density wavenumber spectral coefficient C_n^2 (for details, see e.g. Cordes & Rickett 1998).

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surveys. While an investigation of event rates was recently carried out by Macquart (2011), the analysis assumed Euclidean geometry, ignoring cosmological effects. The results of Thornton et al. (2013), where significant redshifts ($z \sim 0.7$) are implied by the high DMs, imply that propagation effects in an expanding universe must be taken into account. To begin to characterize this population and make testable predictions, we consider the simplest possible cosmological model in which FRBs are standard candles with constant number density per unit comoving volume. The former assumption is justified for source models in which the energetics do not vary substantially. Along with the latter assumption, as we demonstrate below, this model is eminently testable by ongoing and future fast-sampling radio surveys.

Considering the sources as standard candles implies that, for a given survey at some frequency ν, there is a unique correspondence between the observed flux density and redshift probed. To simplify matters, we consider a model in which the pulses have a top-hat shape with some finite width. As we show below, under these assumptions, the flux density–redshift relationship is independent of pulse width. To derive this relationship, we use standard results (e.g. Hogg 1999) and adopt a flat universe where, for a source at redshift z, the comoving distance

$$D(z) = \frac{c}{H_0} \int_0^z \frac{\mathrm{d}z'}{\sqrt{\Omega_\mathrm{m}(1+z')^3 + \Omega_\Lambda}}. \quad (3)$$

Here c is the speed of light, H_0 is the Hubble constant and the dimensionless parameters Ω_m and Ω_Λ represent the total energy densities of matter and dark energy, respectively. Following the latest results from *Planck* (Ade et al. 2013), we adopt a flat universe in which $H_0 = 68\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_\mathrm{m} = 0.32$ and $\Omega_\Lambda = 0.68$. To obtain the peak flux density $\bar{S}_\mathrm{peak}$ averaged over a certain bandwidth at some frequency ν, we model the energy released per unit frequency interval in the rest frame, $E_{\nu'}$, using the power-law relationship

$$E_{\nu'} = k\nu'^{\alpha}, \quad (4)$$

where k is a constant, ν' is the rest-frame frequency and α is a spectral index. Assuming a top-hat pulse of width W' in the rest frame of the source, from conservation of energy, for an observation over some frequency band between ν_1 and ν_2, we may write

$$\bar{S}_\mathrm{peak} 4\pi D_L^2 (\nu_2 - \nu_1) = \frac{\int_{\nu_1'}^{\nu_2'} E_{\nu'} \mathrm{d}\nu'}{W'}, \quad (5)$$

where the luminosity distance $D_L = (1 + z)D(z)$. It is worth noting here that the $(\nu_2 - \nu_1)$ term on the left-hand side of this expression reflects the fact that the pulse has been obtained by dedispersion over this finite observing band. The measured quantity, $\bar{S}_\mathrm{peak}$ is therefore

$$\bar{S}_\mathrm{peak} = \frac{1}{\nu_2 - \nu_1} \int_{\nu_1}^{\nu_2} S(\nu)\mathrm{d}\nu, \quad (6)$$

where $S(\nu)$ represents the flux density per narrow frequency channel within the band. On the right-hand side of equation (5), $\nu_1' = (1 + z)\nu_1$ and $\nu_2' = (1 + z)\nu_2$ are the lower and upper extent of the observing band in the rest frame of the source. Using these identities, and integrating equation (5) for the case where $\alpha \neq -1$, we find

$$\bar{S}_\mathrm{peak} = \frac{k(1+z)^{\alpha-1}(\nu_2^{\alpha+1} - \nu_1^{\alpha+1})}{4\pi D(z)^2\, W'(\nu_2 - \nu_1)(\alpha + 1)}. \quad (7)$$

To write equation (7) in terms of a luminosity model, we note that the bolometric luminosity

$$L = \frac{\int_0^\infty E_{\nu'}\mathrm{d}\nu'}{W'} = \frac{k\left(\nu'^{\alpha+1}_\mathrm{high} - \nu'^{\alpha+1}_\mathrm{low}\right)}{W'(\alpha+1)}, \quad (8)$$

where the model parameters ν'_low and ν'_high are, respectively, the lowest and highest frequencies over which the source emits. Combining these last two equations to eliminate $k/[W'(\alpha + 1)]$, we find

$$\bar{S}_\mathrm{peak} = \frac{L(1+z)^{\alpha-1}}{4\pi D(z)^2 \left(\nu'^{\alpha+1}_\mathrm{high} - \nu'^{\alpha+1}_\mathrm{low}\right)} \left(\frac{\nu_2^{\alpha+1} - \nu_1^{\alpha+1}}{\nu_2 - \nu_1}\right). \quad (9)$$

To calibrate this flux–redshift relationship, based on the results of Thornton et al. (2013), we adopt $\bar{S}_\mathrm{peak} = 1$ Jy at $\nu = 1.4$ GHz at $z = 0.75$ and assume a spectral index $\alpha = -1.4$ which would be appropriate if the emission process is coherent, as observed for the radio pulsar population (Bates, Lorimer & Verbiest 2013). With this choice of parameters, and adopting $\nu'_\mathrm{low} = 10$ MHz and $\nu'_\mathrm{high} = 10$ GHz, we require the bolometric luminosity $L \simeq 8 \times 10^{44}\ \mathrm{erg\,s^{-1}}$. Due to the normalization, the exact choice of ν'_low and ν'_high do not significantly affect the rate calculations given below. The results of this procedure, at 1400, 350 and 150 MHz, with respective bandwidths of 350, 100 and 50 MHz are shown in Fig. 2. The spectral indices of FRBs are currently not well constrained. Thornton et al. see no significant spectral evolution within their 340 MHz bandwidth. If this turns out to be the case over a broader frequency range, then these extrapolated curves are overestimates of the expected flux density and the 1400 MHz curves in Fig. 2 would be more appropriate.

Based on their results, Thornton et al. (2013) compute an event rate, R, of $10\,000^{+6000}_{-5000}$ bursts per day over the whole sky above 1 Jy at 1400 MHz. In our model, where all bursts are sampled out to a redshift of 0.75, it is straightforward to scale this rate to other redshifts via the ratio of the comoving volume $V(z) = (4/3)\pi D(z)^3$ enclosed compared to that at $z = 0.75$. The rate–redshift relationship is therefore $R(z) = R_{0.75}V(z)/V_{0.75}$, where $R_{0.75}$ is the Thornton et al. rate at $z = 0.75$, and $V_{0.75}$ is the comoving volume out to $z = 0.75$. The results of this calculation are shown as a function of z in Fig. 2. Also shown are the predicted rates as a function of threshold flux density and survey frequency.

4 DISCUSSION

The model presented in the previous section and shown in Fig. 2 makes a number of testable predictions for ongoing and planned radio surveys. Within the rate uncertainties found by Thornton et al. (2013), assuming sensitivity out to some z, fitting a cubic to the centre panel of Fig. 2 provides the following good approximation to the expected event rate out to $z = 1$:

$$R(<z) \simeq \left(\frac{z^2 + z^3}{4}\right)\ \mathrm{d^{-1}\,deg^{-2}}. \quad (10)$$

An important constraint for our model is that it should be consistent with ongoing surveys at 1.4 GHz where assumptions about the source spectral index are not required. Currently, the most sensitive fast transient search at 1.4 GHz is the ongoing Pulsar Arecibo *L*-band Feed Array (PALFA) survey (Cordes et al. 2006; Deneva et al. 2009) which has so far found no FRBs. Through detailed considerations, Deneva et al. (2009) quantify the effects of the greater depth probed by the PALFA survey and its smaller field of view. A comparison of the solid curve shown in the right-hand panel of Fig. 2 of this Letter and fig. 8 from Deneva et al. (2009) shows that

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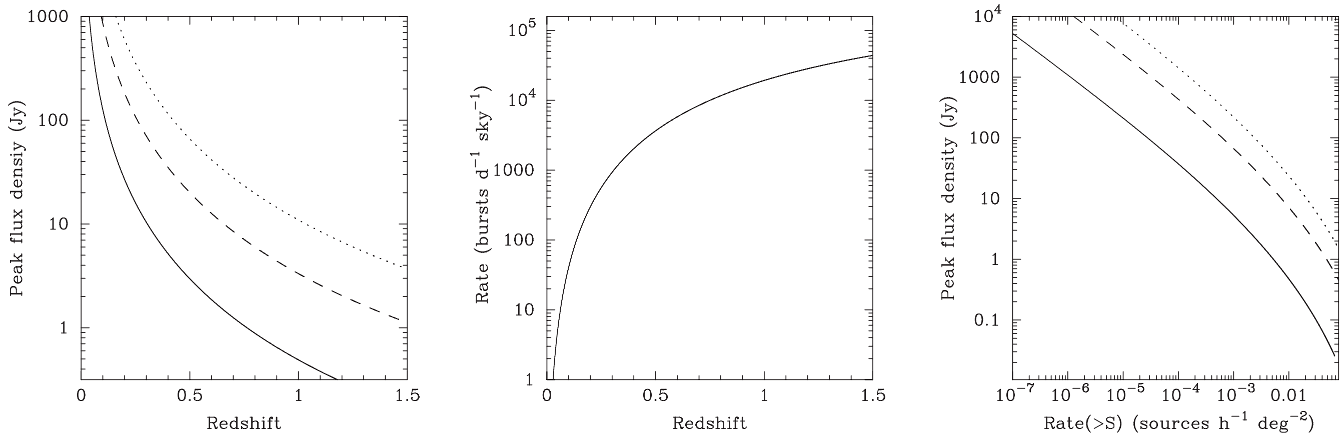

Figure 2. Predictions from our FRB population model. The left-hand panel shows flux–redshift relationships for surveys carried out at 1400 (solid line), 350 (dashed line) and 150 MHz (dotted line). The centre panel shows the event rate normalized such that at $z = 0.75$ the implied event rate is 10 000 FRBs per day per sky as inferred by Thornton et al. (2013). The right-hand panel shows the predicted burst rates above some threshold flux density S at 1400 (solid line), 350 (dashed line) and 150 MHz (dotted line).

our model is currently not excluded by the lack of detections in the PALFA survey. Our model is also consistent with the 'Fly's Eye' survey carried out with the Allen Telescope Array (ATA) by Siemion et al. (2012) which was sensitive to pulses with peak fluxes >150 Jy (assuming a 3 ms pulse width). Our predicted rate of a few times 10^{-6} FRBs h^{-1} deg^{-2} is below the ATA upper limit of 2×10^{-5} FRBs h^{-1} deg^{-2}.

Furthermore, bursts are expected in the other 1.4 GHz multibeam surveys. In the Parkes multibeam pulsar survey (Manchester et al. 2001), where only one FRB candidate has so far been found (Keane et al. 2012), a simple scaling of the Thornton et al. (2013) rate leads to around 5–15 bursts in the existing data. While a recent re-analysis by Bagchi, Nieves & McLaughlin (2012) did not find any candidates in the DM range 200–2000 cm^{-3} pc in addition to the Keane et al. event, the survey coverage along the Galactic plane may imply that searches covering higher DM ranges are necessary. A search of archival data from the Edwards et al. (2001) and Jacoby et al. (2009) intermediate and high latitude surveys by Burke-Spolaor & Bailes (2010) revealed a number of rotating radio transients, but no new FRBs. However, the DM range covered in this effort (0–600 cm^{-3} pc) was likely not sufficient to sample a significant volume, based on the results presented here. We suggest that reanalyses of these data sets may result in further FRB discoveries. We note also that the substantial amount of time spent and field of view covered by the High Time Resolution Universe-North survey at Effelsberg (Barr et al. 2013) mean around 20 FRBs are expected.

At 350 MHz, a significant fraction of the transient sky is currently being covered by pulsar searches with the GBT. The drift-scan survey carried out during summer 2007 (Boyles et al. 2013; Lynch et al. 2013; Rosen et al. 2013), acquired a total of 1491 h of observations and has so far discovered 35 pulsars. Based on the survey parameters given by Lynch et al. (2013), we estimate the instantaneous field of view to be about 0.3 deg^2 and the 10σ sensitivity for pulses of width 3 ms to be about 35 mJy. As can be inferred from Fig. 2, a source at this frequency is predicted to have a peak flux well in excess of this threshold even out to $z > 1$. As shown in Fig. 1, the expected scattering of an FRB at 350 MHz should be below 10 ms for a DM of a few hundred cm^{-3} pc. Adopting a DM limit of 500 cm^{-3} pc, and assuming about 20 per cent of this DM is accounted for by the host galaxy and the Milky Way, from the approximate intergalactic medium scaling law (where DM $\sim 1200z$ cm^{-3} pc Ioka 2003; Inoue 2004), we expect a redshift limit of 0.33. From equation (10), we infer a rate of about 4×10^{-4} bursts per 0.3 deg^2 per hour, or of the order of one FRB in the entire survey. Since the GBT survey is not sensitivity limited and the steep gradient seen in the centre panel of Fig. 2, this prediction is subject to considerable uncertainty. A further more sensitive GBT search is now underway with the aim of covering the entire GBT sky (Stovall et al., in preparation). A comprehensive analysis of these data, and ongoing Arecibo 327 MHz surveys (Deneva et al. 2013) should provide interesting constraints on the FRB population. If the same DM limit can be reached by 150 MHz surveys with large fields of view, the expected detection rate above 30 Jy with DMs below 500 cm^{-3} pc is ∼1 event per day per 30 square degrees.

5 CONCLUSIONS

We have used the results of Thornton et al. (2013) to calibrate a cosmological model which predicts the rate of FRBs as a function of redshift. Our assumption of uniform source density with comoving volume implies a significant population of bursts detectable at moderate to low redshifts by low-frequency ($\nu < 1$ GHz) surveys. Moreover, our assumption that the bursts are standard candles implies that such events should be bright (10 s of Jy or more) and would be readily detectable by instruments with modest collecting areas. Both of these assumptions can be tested by ongoing and future surveys.

An important conclusion from this work is that low-frequency surveys should sample as large a DM range as possible, and search for pulses over a wide range of widths. An additional simplification we have made is that the source spectra follow a power law with slope of –1.4. The event rates predicted here will differ significantly if the spectrum deviates from this form. Many of the current ongoing surveys and other large-scale surveys expected over the next few years with LOFAR (Stappers et al. 2011), the Murchison Widefield Array (MWA; Tingay et al. 2013) and the Australian Square Kilometre Array Pathfinder (Macquart et al. 2010), and other facilities, will undoubtedly find more FRBs and test the predictions presented here.

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