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Constraints on the FRB rate at 700-900 MHz

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ABSTRACT

Estimating the all-sky rate of fast radio bursts (FRBs) has been difficult due to small-number statistics and the fact that they are seen by disparate surveys in different regions of the sky. In this paper we provide limits for the FRB rate at 800 MHz based on the only burst detected at frequencies below L-band, FRB 110523. We discuss the difficulties in rate estimation, particularly in providing an all-sky rate above a single fluence threshold. We find an implied rate between 700-900 MHz that is consistent with the rate at 1.4 GHz, scaling to $8.9^{+40.7}_{-6.7} \times 10^3\,\mathrm{sky}^{-1}\,\mathrm{day}^{-1}$ for an HTRU-like survey. This is promising for upcoming experiments below L-band like CHIME and UTMOST, for which we forecast detection rates. Given 110523's discovery at 32σ with nothing weaker detected, down to the threshold of 9σ, we find consistency with a Euclidean flux distribution but disfavour steep distributions.

Key words: methods: statistical, pulsars: general

1 INTRODUCTION

A new class of radio transients known as fast radio bursts (FRBs) has been discovered in the last decade. FRBs are highly dispersed millisecond events whose origin remains unknown. Their large dispersion measures (DM $\sim$ 360-1600 pc cm^{-3}) imply they come either from cosmological distances ($z \sim 0.3$-1) or regions of over-dense plasma. They occur with frequency of thousands per sky per day but the volumetric rate this implies depends strongly on whether the large DM observed resides in the intergalactic medium (IGM) or the host galaxy. If the dispersion occurs in the IGM the sources are at cosmological distances and the FRB rate is within a couple orders of magnitude of the core-collapse supernova rate for a cosmological population. If not, FRBs are still likely extragalactic but non-cosmological.

To date, estimating the all-sky rate of FRBs has proven difficult, even at 1.4 GHz where most have been found (Thornton et al. 2013; Petroff 2014; Champion et al. 2015; Spitler et al. 2014). This is in part because of their unknown flux distribution and location within the radio telescope beam, as well as the low number of observed events. It is further exacerbated by the different specifications of the surveys that find them, whose disparate search algorithms, fluence completenesses, and sensitivity can affect their detection rate. Extrapolating to other frequencies is also difficult since spectral indices and the extent of scattering are still unknown.

Thornton et al. (2013) searched about 25% of the High Time Resolution Universe (HTRU) survey data and found four FRBs. They estimated an all-sky daily rate of $1.0^{+0.6}_{-0.5} \times 10^4$ above $\sim$ 3 Jy ms from 23 days of data and using a 0.55 deg^2 beam. The rate based on HTRU has since come down ($6^{+4}_{-3} \times 10^3$ sky^{-1} day^{-1}) with the discovery of five more FRBs in three times as much data (Champion et al. 2015). Keane & Petroff (2015) also found a rate that was lower than the initial estimate, calculating $\sim$ 2500 sky^{-1} day^{-1} after accounting for completeness factors like fluence sensitivity. Though the error bars are still significant, there is some convergence on the rate, and it now seems likely that there are thousands of such events each day at 1.4 GHz.

Event rate estimates at 1.4 GHz are converging, but strong rate constraints have not yet been made in other bands. The non-detection by UTMOST (Caleb et al. 2016)

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placed a 2σ upper limit on the number of bright events (10^3 events per sky per day above 11 Jy ms) after searching 467 hours at a fraction of its eventual sensitivity. FRB 110523 remains the only published event not found in L-band (1-2 GHz). It was found near 800 MHz, where scattering or the intrinsic spectral index might have rendered this lower-frequency FRB unobservable. Kulkarni, Ofek & Neill (2015) argued that the steep blue spectrum seen in FRB 121102 (Spitler et al. 2014) was indicative of free-free absorption, the optical depth of which scales as $\lambda^{2.1}$ and would make metre-wave bursts difficult to see. A greater concern comes from scattering. Sources broadened by scattering to ~ 10 ms at 1.4 GHz would be ~ 100 ms at 800 MHz, and a couple of seconds at 400 MHz, due to the λ^4 scaling of the scattering width.

Some surveys that could have great impact on FRB science are threatened by strong scattering. ALERT hopes to localize dozens of bursts with LOFAR after finding them with the large field-of-view (FoV) APERTIF (Verheijen et al. 2008), UTMOST will have ~ 8 deg^2 of sky coverage 24/7 at 843 MHz (Caleb et al. 2016), and HIRAX, Tianlai[1] and CHIME (400-800 MHz) could see 10^{2-4} per year, with the ability to write full polarization information (Bandura 2014). However, their success depends on whether or not the rate of detectable FRBs is comparable to that at higher frequencies.

2 FLUX DISTRIBUTION

FRB 110523 was found by searching data from the Green Bank Hydrogen Intensity Mapping (GBTIM hereon) survey (Chang et al. 2010; Masui et al. 2015; Switzer et al. 2013). These data were taken with 1.024 ms cadence between 700-900 MHz using the GBT linearly-polarized prime-focus 800 MHz receiver, along with the GBT Ultimate Pulsar Processing Instrument (GUPPI) digital back-end. An effective DM range of 20-2000 pc cm^{-3} was then searched for FRBs. At each DM, the data were convolved with all possible lengths of top-hat windows up to 200 ms to search for peaks. The peaks were then compared to the root mean square (RMS) of the convolved time-stream, the ratio of which is what we will refer to as signal-to-noise ratio (SNR). The survey duration was 660 hours.

In order to test the observed FRB flux distribution, $N(F)$, we can apply a standard log(N)-log(F) test. We will consider only power-law distributions of form $N(>F) \propto F^{-\gamma}$. In a Euclidean Universe a population of sources that are uniformly distributed in space should have $N(>F) \propto F^{-3/2}$. This makes intuitive sense, since number counts ought to increase like the cube of distance, while the flux falls off as inverse squared distance.

With no FRBs found between the search algorithm's detection threshold, 9σ, and 32σ, where FRB 110523 was found, we can test if this has any implications for the true flux distribution. The question we are trying to answer is "Having seen a single event, what is the probability that it has SNR greater than s for a given value of γ?". This is

[1] http://tianlai.bao.ac.cn/

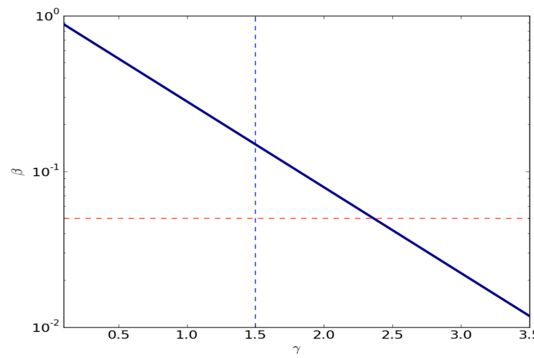

Figure 1. Probability for the one observed FRB to have SNR equal or larger to the observed value of $s = 32$, as a function of the power-law index, γ. The red horizontal line is at .05, below which models can be ruled out with 95% confidence (this happens for $\gamma \gtrsim 2.3$). The blue vertical line is at the standard Euclidean value of 1.5, which cannot be ruled out.

given by the ratio of integrals,

$$\beta \equiv \frac{\int_{s_{\max}}^{s_\infty} N(s)ds}{\int_{s_{\min}}^{\infty} N(s)ds}, \quad (1)$$

which reduces to $\beta = \left(\frac{s_{\max}}{s_{\min}}\right)^{-\gamma}$ for $\gamma \neq 0$ and integrands of the form $N(s) \propto s^{-\gamma-1}$. We plot this statistic in Figure 1 as a function of γ and show that steep distributions with $\gamma > 2.3$ are disfavoured by this single detection alone.

This is mathematically equivalent to the single-burst solution to a more general approach similar to the biased coin-flip scenario outlined by Connor, Pen & Oppermann (2016). If $M_{\rm high}$ FRBs are observed above a threshold SNR of $s_{\rm thresh}$, with $M_{\rm tot}$ above $s_{\rm min}$, and p is the relative probability of detecting an FRB in the high-SNR region, then

$$P(M_{\rm high}|\, M_{\rm tot}, p) = \binom{M_{\rm tot}}{M_{\rm high}} p^{M_{\rm high}} (1-p)^{M_{\rm tot}-M_{\rm high}}, \quad (2)$$

where p is just $\beta(\gamma)$. Clearly this reduces to the previous result in the case where $M_{\rm high} = M_{\rm tot} = 1$.

3 RATES

The simplest constraints one can make, given a set of observations, will be an expected event rate for a future survey with identical parameters. Transferring that rate to another survey or onto the sky requires care, and in both cases uncertainties are introduced that are hard to quantify. For this reason we start by calculating a rate for GBTIM in Sect. 3.1, which predicts how many FRBs are expected if an identical survey were to take place again. After that we discuss the implications for other comparable surveys, which should be fairly robust against things like burst-width sensitivity and the choice of fluence thresholds. In Sect. 3.3 we provide an all-sky rate, with several caveats, and discuss the meaning of such a value.

3.1 Burst rate

The rate of FRBs implied by 110523 will be independent of its observed brightness. The relevant quantity is the survey sensitivity, so $s_{\min}$ is the only flux scale that should show up in our rate estimate. For a true rate μ_0 above $s_{\min}$, we would expect the number of bursts, M, in a given survey above some SNR, s, to be

$$M_s = \mu_0 \, \Omega \, T_{\rm int} \frac{N(> s)}{N(> s_{\min})}, \tag{3}$$

where Ω is the telescope's FoV and $T_{\rm int}$ is the time on sky. We use the rate above some SNR so that we can easily scale it to a rate prediction for a different survey without making any implicit assumption about the distribution of FRBs in flux, fluence, or duration. Similar to Eq. (1), this becomes

$$M_s = \mu_0 \, \Omega \, T_{\rm int} \frac{s^{-\gamma}}{s_{\min}^{-\gamma}} \quad \text{for } \gamma > 0. \tag{4}$$

However, since we will not try to estimate an all-sky daily rate until Sect. 3.3, for now we will take $T_{\rm int}$ and Ω to be in units of the GBTIM on-sky time and beam-size. Therefore M_s should be thought of as the number of FRBs one would expect if the GBTIM were repeated.

3.1.1 Frequentist rate limits

If we regard the sky rate μ_0 as fixed, we can immediately write down the probability of observing $M_{\rm tot}$ FRBs above a SNR of s. It is simply given by the Poissonian distribution

$$P(M_{\rm tot}|\mu_0) = \frac{M_{s_{\min}}^{M_{\rm tot}} \mathrm{e}^{-M_{s_{\min}}}}{M_{\rm tot}!}, \tag{5}$$

where $M_{s_{\min}}$ is given by Eq. (4) for $s = s_{\min}$. Now we can ask which values of M_s make the observed value of $M_{\rm tot} = 1$ unlikely. Choosing a threshold value of 5%, we can—in this sense—rule out expected event counts $M_{s_{\min}}$ outside of the range from 0.05-4.50 events per GBTIM-like survey, with a maximum likelihood value at 1.

3.1.2 Bayesian rate limits

From a Bayesian viewpoint, we want to look at the posterior for the expected number of detections, $M_{s_{\min}}$ rather than the likelihood. For simplicity we choose a flat prior on $M_{s_{\min}}$, which means that the posterior is again

$$\mathcal{P}(M_{s_{\min}}|M_{\rm tot}) = \frac{M_{s_{\min}}^{M_{\rm tot}} \mathrm{e}^{-M_{s_{\min}}}}{M_{\rm tot}!}. \tag{6}$$

Note that, although the posterior has the same functional form as the likelihood, it is to be read as a density in $M_{s_{\min}}$ rather than a probability for $M_{\rm tot}$. Now we can calculate another 95% confidence interval, defined as the smallest interval I with the property $\int_I \mathrm{d}\mu_0 \, \mathcal{P}(\mu_0|M_{\rm tot}) = 0.95$. We find for this 95% confidence interval $I = [0.24, 5.57]$ events for a GBTIM-like survey. From hereon we will quote the rate error bars based on the posterior. The posterior for μ_0, which is the same as Eq. (6) multiplied by $\Omega \, T_{\rm int}$, is shown in Fig. 2.

3.2 Implications for other surveys

Though only one event was observed in the 660 hours of archival data, the fact that any burst was detectable in this band is significant. Some of the most important upcoming surveys for FRB science will observe below L-band. UTMOST (Caleb et al. 2016) will be on the sky 24/7 with an ~ 8 deg^2 FoV and 18,000 m^2 of collecting area, observing at 843 MHz. ALERT hopes to localize dozens of FRBs by first detecting them with the large-FoV APERTIF (Verheijen et al. 2008) and then following up with roughly arcsecond resolution when they arrive several minutes later at LOFAR. Another survey for which FRB 110523's discovery is relevant is CHIME, observing at 400-800 MHz. If the event rate in this band is comparable to the one at higher frequencies, then its large FoV and uninterrupted observing will make it by far the fastest FRB survey.

Since the rate of detection depends on an interplay of the underlying FRB flux and scattering distributions with a survey's thermal sensitivity, fluence completeness, and observing frequencies, the comparison of two surveys with similar specifications is by far the safest bet. CHIME has $\sim 8,000$ m^2 of collecting area compared to GBT's $\sim 7,850$ m^2 and has 100 MHz of overlap with GBTIM. UTMOST will observe within the GBTIM band with similar sensitivity per steradian. Though others (Burke-Spolaor & Bannister 2014) have provided models for calculating inter-survey sensitivity based on sky pointing and temporal broadening, we compare only similar telescopes and adopt the simplest possible comparison based on known features of each instrument. Given how little is known about scattering properties and spectral indices, we provide only a skeleton model below; a more detailed calculation is beyond the scope of this paper.

A survey, Σ, that is similar to the GBTIM experiment will see N_Σ events per day based on the one detected burst in ~ 27.5 days at GBT. This is given by

$$N_\Sigma = \frac{1}{27.5} \left(\frac{G_\Sigma}{G_{\rm GBT}} \frac{\langle T^{\rm sys}_{\rm GBT} \rangle}{\langle T^{\rm sys}_{\Sigma} \rangle} \sqrt{\frac{B_\Sigma}{B_{\rm GBT}}} \right)^{\gamma} \left(\frac{\Omega_\Sigma}{\Omega_{\rm GBT}} \right) \mathrm{day}^{-1} \tag{7}$$

where B gives the survey's bandwidth, G is the gain, and $\langle T^{\rm sys} \rangle$ gives the pointing-averaged system temperature. For GBT we take the effective solid angle based on the full-width half max (FWHM) in power, giving $\Omega_{\rm GBT} \sim 0.055$ deg^2. We use 26.5 K for the sky-averaged system temperature, and a gain of 2 K Jy^{-1}.

As discussed above, in assessing the impact FRB 110523's detection on other surveys, we want to avoid venturing into the unknown. For this reason we consider only the 100 MHz of overlap between CHIME and GBTIM, since that region is known to have a non-zero rate of observable FRBs. For things like beam size, we take the maximum possible FoV based on CHIME's optics and let others adjust the effective solid angle accordingly; though the CHIME collaboration may search only a subset of their primary beam in order to optimize other aspects of their FRB survey, we will estimate the rate based on a full beam.

We model CHIME's primary beam at 750 MHz based on Shaw et al. (2015). A simple dipole beam in the aperture plane is propagated onto the sky by treating the reflector along the cylinder (north-south direction) as a mirror, and by solving the Fraunhofer diffraction problem in the east-west direction. As with GBT, we use only the beam within the half-max contour. This gives $\Omega_{\rm CH} \sim 86$ deg^2 in the middle of its band compared to $\Omega_{\rm GBT} \sim 0.055$ deg^2. Though this gives a ratio of $\sim$ 1600 between the two telescope's beam sizes, we remind the reader that this is an approximate solid-angle upper-limit for CHIME between 700-800 MHz. We then estimate its aperture efficiency as 50%, compared with 72% at GBT[2], whose feed horn maximally illuminates its dish while minimizing ground spill, something that is difficult with CHIME's dipole antennas. This makes $G_{\rm CH} = 1.38$ K Jy^{-1}. Finally, keeping with 26.5 K for GBT's system temperature as before and using CHIME's design system temperature of 50K (Bandura 2014), we can write the maximum-likelihood value for the CHIME rate as

$$N_{\rm CH} \approx 7.5 \left(\frac{50\,{\rm K}}{T^{\rm sys}} \right)^{1.5} {\rm day}^{-1} \tag{8}$$

assuming a Euclidean distribution. This means with a 50 K system temperature, CHIME could see between 2-40 (95%) bursts per day if it searches its whole FoV, based on the known non-zero rate above 700 MHz. With a more conservative sky-averaged system temperature $T^{\rm sys} = 100$ K, CHIME might expect between one every couple of hours and one every two days.

Caleb et al. (2016) estimate the daily rate of UTMOST in a similar way, directly comparing their sensitivity with that of Parkes at 1.4 GHz. They estimate that they will see a burst once every several days. However, with our constraints on the rate between 700-900 MHz, we can recompute UTMOST's detection rate based on the same band, once it reaches final sensitivity. We use $G = 3.6$ K Jy^{-1}, $T^{\rm sys} = 70$ K, $B = 31.25$ MHz, and a factor of $1/\sqrt{2}$ for its single polarization, based on Caleb et al. (2016). This gives $4.2^{+19.6}_{-3.2} \times 10^{-1}$ day^{-1}, or between a couple per day and one every couple of weeks. This is consistent with Caleb et al. (2016).

3.3 All-sky daily rate

The standard method for estimating an all-sky rate given a set of observations is to first calculate the rate, μ_0, for that survey — usually the observed number of FRBs divided by the beam size and the time on sky — and then to scale that based on the survey's sensitivity threshold and a flux distribution index, γ. This threshold has typically been in fluence, a physically motivated quantity for FRBs, and is given by

$$H_{\rm min} = \frac{s_{\rm min} \left\langle T^{\rm sys} \right\rangle \tau}{G\sqrt{m\tau B}}, \tag{9}$$

where $\langle T^{\rm sys} \rangle$ is the pointing-averaged system temperature, as before, $s_{\rm min}$ is the SNR threshold used in the search algorithm, G is the gain at beam centre, B is the bandwidth, m gives the number of polarizations, and τ is some timescale. If one then wants to quote the rate above, say, 3 Jy ms, then the rate becomes $\mu \times \left(\frac{H_{\rm min}}{3\,{\rm Jy\,ms}} \right)^{\gamma}$.

[2] https://science.nrao.edu/facilities/gbt/proposing/GBTpg.pdf

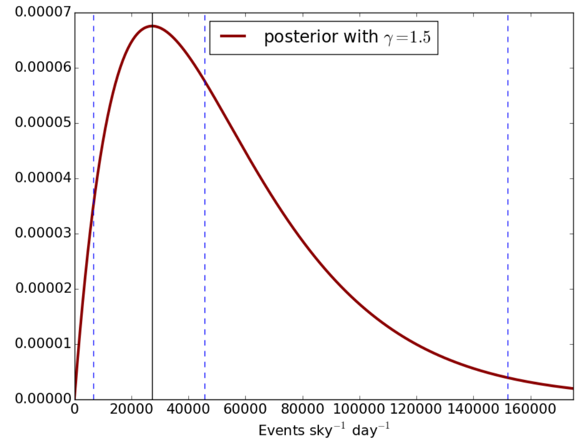

Figure 2. Posterior distribution for the all-sky daily rate based on seeing one burst in 27.5 days of data with a 0.055 deg^2 beam. This posterior is meant to be interpreted as the number of FRBs one would see if GBTIM-like surveys were able to observe the whole sky for a day, i.e. we have not scaled the rate based on fluence sensitivity for reasons described in Sect. 3.3. The maximum a posteriori value is denoted by the black vertical line, which is at $\sim 2.7 \times 10^4$ sky^{-1} day^{-1}. The two outside blue lines enclose 95% of the curve and the middle blue line denotes the median.

One problem with this method is that it is not entirely obvious how to choose τ, and several groups have approached it differently. Keane & Petroff (2015) discuss some of these effects and decided to use the value at which their survey becomes fluence complete, 2 Jy ms, based on the maximum width to which they are sensitive. Rane et al. (2016) use sampling time, which is the minimum possible effective burst width, but this will maximize the reported search sensitivity and therefore generically lower the final rate estimate. A more exact approach is to quote the rate above some fluence curve $H \propto \sqrt{\tau}$ between $\tau_{\rm min}$ and $\tau_{\rm max}$ corresponding to the actual SNR threshold if white noise is assumed. This is similar to what Champion et al. (2015) do, who quote their rate above a fluence range.

Since the primary goal of this paper is to compare between surveys, we do not attempt to derive a strict fluence threshold for GBTIM and to scale our all-sky rate based on it. Until the fluence and width distributions for FRBs are known along with a search algorithm's width response, the all-sky rate quoted for some incomplete region of fluence space is not overly useful. Instead, we calculate the rate above our true threshold, which is $s_{\rm min} = 9$ for DMs between 20-2000 pc cm^{-3} and widths between one and two hundred milliseconds. A useful estimate of the rate is given by the maximum of Eq. (6), $\mu_0 = \frac{1}{\Omega\, T_{\rm int}} \left(\frac{s}{s_{\rm min}} \right)^{\gamma}$, for $s = s_{\rm min}$. The all-sky rate for GBTIM above 9σ is then $2.7^{+12.4}_{-2.1} \times 10^4$ sky^{-1} day^{-1}, between 700-900 MHz. We plot the corresponding posterior in Fig. 2.

Though this value seems high, GBTIM is a sensitive survey, with $F_{\rm min} = 0.11$ Jy for a 3 ms pulse. Without making any concrete statements about our sensitivity in fluence space, we can get an idea of how this rate compares to the estimates from other surveys based only on thermal sensitivity. We can use the rate inferred from the 9 HTRU FRBs as a baseline (Champion et al. 2015). If we assume the width completeness of various surveys is roughly similar, we can tether our rate to the HTRU one, and calculate a sensitivity ratio, r_s. Comparing Parkes and GBT, this will be

$$r_s = \frac{\langle T_{\rm H}^{\rm sys} \rangle}{\langle T_{\rm GBT}^{\rm sys} \rangle} \frac{G_{\rm GBT}}{G_{\rm H}} \sqrt{\frac{B_{\rm GBT}}{B_{\rm H}}} \frac{s_{\rm min}^{\rm H}}{s_{\rm min}^{\rm GBT}}. \tag{10}$$

Using $s_{\rm min}^{\rm H} = 10$, $G_{\rm H} = 0.735\,{\rm K\,Jy^{-1}}$, $B_{\rm H} = 340\,{\rm MHz}$, and a 23 K system temperature (Keith et al. 2010), we find $r = 2.01$. Our rate can then by multiplied by $r^{-\gamma}$, which gives $8.9^{+40.7}_{-6.7} \times 10^3\,{\rm sky^{-1}\,day^{-1}}$, assuming a Euclidean distribution.

This is an extrapolation of our rate estimate at 700-900 MHz to 1.4 GHz. It corresponds to the number of FRBs that HTRU should be detecting if the intrinsic rates of FRBs in the two frequency bands were the same. This extrapolated rate is indeed consistent with the rate observed by HTRU, which shows that the rate of FRBs detectable at low frequencies is not significantly lower than at L-band, which was not previously obvious due to the threat of scattering and steep blue power-laws (Kulkarni, Ofek & Neill 2015). This result makes the aforementioned upcoming low-frequency surveys especially promising for FRB science.

This is also consistent with the non-detection upper-limit set by Caleb et al. (2016), who found the rate to be below $10^3\,{\rm sky^{-1}\,day^{-1}}$ for one-millisecond 11 Jy bursts at the 2σ level. This was based on two surveys, one with 467 hours on sky, and another with 225 hours on sky at roughly twice the sensitivity. Comparing their time-weighted thermal sensitivity with GBTIM, we get $r_s \approx 10^2$, making our 95% upper-limit a few hundred per sky per day.

4 CONCLUSIONS

FRB 110523 is the only FRB to be observed below 1.4 GHz. Its detection is encouraging because there are several upcoming surveys below L-band whose impact on FRB science is hard to overestimate, so long as the transients are detectable at low frequencies. In the next several years CHIME, HIRAX, Tianlai, UTMOST, and ALERT could increase the number of detected FRBs by orders of magnitude, provide polarization information and repetition statistics, and localize them. In this paper we have provided the first detailed bounded constraints on the FRB rate below L-band.

We have shown two ways of estimating the rate given the detection of FRB 110523, one based on a frequentist hypothesis test, and the other done in a Bayesian framework. These give the same maximum-likelihood value, but somewhat different 95% confidence intervals. We have then used the GBTIM estimate to forecast rates for CHIME and UTMOST, explicitly only comparing surveys with similar specifications. We find CHIME could detect between 2 and 40 per day, given by $\approx 7.5 \left(\frac{50\,{\rm K}}{T^{\rm sys}}\right)^{1.5}\,{\rm day^{-1}}$, making it the fastest upcoming survey. UTMOST, which observes in a band inside GBTIM's and whose sensitivity per steradian should eventually be comparable, could see between a couple per day and one every two weeks.

The difficulties of estimating an all-sky rate above a single fluence value was discussed. We showed how an on-sky rate not attached to a specific survey is not only hard to predict but also hard to interpret. For that reason we estimated a rate above the true threshold for GBTIM — an SNR of 9 — which gave us $2.7^{+12.4}_{-2.1} \times 10^4\,{\rm sky^{-1}\,day^{-1}}$. The fluences to which GBTIM was sensitive are those above the curve $0.19\sqrt{(\tau/{\rm ms})}\,{\rm Jy\,ms}$ for pulse widths between 1-200 ms. To test the agreement between this rate and those found by other surveys, we scaled based only on thermal sensitivity. If we extrapolate from this daily rate to a survey with the sensitivity of HTRU, we find $8.9^{+40.7}_{-6.7} \times 10^3\,{\rm sky^{-1}\,day^{-1}}$, which is consistent with (Champion et al. 2015).

We also investigated the flux distribution index, γ, and found that steep distributions with $\gamma > 2.3$ are disfavoured.

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