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A search for highly dispersed fast radio bursts in three Parkes multibeam surveys

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ABSTRACT

We have searched three Parkes multibeam 1.4 GHz surveys for the presence of fast radio bursts (FRBs) out to a dispersion measure (DM) of 5000 pc cm^{-3}. These surveys originally targeted the Magellanic Clouds (in two cases) and unidentified gamma-ray sources at mid-Galactic latitudes (in the third case) for new radio pulsars. In previous processing, none of these surveys were searched to such a high DM limit. The surveys had a combined total of 719 h of Parkes multibeam on-sky time. One known FRB, 010724, was present in our data and was detected in our analysis but no new FRBs were found. After adding in the on-sky Parkes time from these three surveys to the on-sky time (7512 h) from the five Parkes surveys analysed by Rane et al., all of which have now been searched to high DM limits, we improve the constraint on the all-sky rate of FRBs above a fluence level of 3.8 Jy ms at 1.4 GHz to $R = 3.3^{+3.7}_{-2.2} \times 10^3$ events per day per sky (at the 99 per cent confidence level). Future Parkes surveys that accumulate additional multibeam on-sky time (such as the ongoing high-resolution Parkes survey of the Large Magellanic Cloud) can be combined with these results to further constrain the all-sky FRB rate.

Key words: surveys – pulsars: general.

1 INTRODUCTION

In recent years, a number of short-duration (millisecond) radio bursts (‘fast radio bursts’, or FRBs) have been detected by the Parkes, Arecibo, and Green Bank radio telescopes in large-scale pulsar surveys. These bursts have characteristics which indicate that they are not of terrestrial origin and are likely of extragalactic origin. The broad-band dispersion characteristics observed for FRBs very closely obey the cold plasma dispersion law in which the signal delay is proportional to the inverse square of the observing frequency (e.g. Lorimer & Kramer 2005). This is expected if the signal originates from an astrophysical source (unlike, e.g. similar signals detected in some surveys, such as Perytons, which have been identified as terrestrial microwave interference; Petroff et al. 2015b). The FRBs detected to date also have dispersion measures (DMs) significantly larger than what the Galactic plasma content along the line of sight is likely to account for (Cordes & Lazio 2002). This fact, along with the recently proposed association of FRB 150418 with an elliptical galaxy at redshift 0.5 (Keane et al. 2016), suggests that these bursts originate from very large (cosmological) distances. Note, however, that Williams & Berger (2016) and Vedantham et al. (2016) have called into question this association, and other models have been proposed in which the high DM can be accounted for more locally (see, e.g. Connor, Sievers & Pen 2016).

To date, only one of these bursts, FRB 121102 (Spitler et al. 2014), has been observed to repeat (Scholz et al. 2016; Spitler et al. 2016), despite numerous efforts and many hours spent trying to re-detect FRBs in the same sky location using the same observing system. With the possible exception of FRB 150418, no FRBs have yet been localized to the point where associations with known objects can be established. Thus, the physical origin of FRBs remains uncertain, though the repeating nature of at least a subset of FRBs indicates that some of them do not originate from a cataclysmic event that destroys the source object. Models for FRBs such as supergiant pulses emanating from magnetars in other galaxies (e.g. Cordes & Wasserman 2016) are currently favoured. For a recent overview and list of references to a variety of proposed models for FRBs, see Rane et al. (2016) and Katz (2016).

The current tally of FRBs that have been detected and published is presented in the Swinburne FRB Catalogue (Petroff et al. 2016).[1]

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[1] http://www.astronomy.swin.edu.au/pulsar/frbcat/

Table 1. Summary of three Parkes surveys searched.

Survey	SMC	EGU	PLMC
Galactic latitude range	$\|b\| \sim 45°$ (SMC); $\|b\| \sim 53°$ (LMC)	$5° < \|b\| < 73°$	$\|b\| \sim 53°$ (LMC)
Total number of survey beams	2717[a]	3016	520[b]
Integration time per pointing (s)	8400	2100	8600
Total on-sky survey time (hr)	488	135	96[b]
Sampling time (ms)	1.000	0.125	0.512[c]
Number of frequency channels	96	96	870[d]
Observing bandwidth (MHz)	288	288	340[d]
Center observing frequency (MHz)	1374	1374	1352[d]
Max. galactic DM contribution (pc cm^{-3})[e]	∼50	∼500[f]	∼50
Original max. DM searched (pc cm^{-3})[g]	800	1000	500
New max. DM searched (pc cm^{-3})	5000	5000	5000
Number of trial DMs in new search	256	371	1431
Known burst signals detected	1 FRB[h]	1 Peryton[i]	–
Survey references	Manchester et al. (2006) Ridley et al. (2013)	Crawford et al. (2006)	Ridley et al. (2013)

Notes. All three surveys used the 13-beam multibeam receiver (Staveley-Smith et al. 1996) on the Parkes 64-m telescope, and all surveys were conducted at 1.4 GHz. All three surveys therefore had the same beam size and instantaneous sensitivity as other large-scale Parkes surveys recently searched for FRBs.

[a]Our analysis used 2756 beams [2717 original survey beams plus 39 unique extra beams that were not used in the Manchester et al. (2006) survey grid].

[b]This corresponds to the first 20 per cent of the total survey coverage, which is the fraction of the survey that has been observed (and processed) to date.

[c]For the analysis here, the raw time samples were aggregated into groups of eight to create an effective sampling time of 0.512 ms from the native 0.064 ms sampling at the telescope recorder.

[d]The BPSR data recorder used at the Parkes telescope has 400 MHz of bandwidth split into 1024 channels with a 1382 MHz centre observing frequency (Keith et al. 2010). However, the receiver is not sensitive to the top 60 MHz of the band, which is blanked during the data analysis. The table therefore shows the effective values with this 60 MHz band removed.

[e]Maximum Galactic DM contribution estimated from the NE2001 Galactic electron model (Cordes & Lazio 2002) for all survey lines of sight.

[f]The expected maximum Galactic DM along the line of sight is $\lesssim$100 pc cm^{-3} for more than half of the target sources in this survey, and no lines of sight have an expected maximum Galactic DM greater than 500 pc cm^{-3}.

[g]Maximum DM searched for pulsars and impulsive signals in the original survey analysis.

[h]FRB 010724 was discovered by Lorimer et al. (2007) in this survey with DM = 375 pc cm^{-3} (see Fig. 1). This signal was detected in our analysis.

[i]1 Peryton was discovered by Burke-Spolaor et al. (2011) which had a fitted DM ∼ 375 pc cm^{-3}. This signal was detected in our analysis (see Fig. 1), but it has been determined to be terrestrial in origin (Petroff et al. 2015b).

All but two of these FRBs were detected with the Parkes 64-m telescope, and all but one have been detected at or near an observing frequency of 1400 MHz. Efforts are now underway both to comb existing pulsar survey data for FRBs that may have been missed in previous analyses of the data and to detect FRBs as they occur using real-time observing and detection systems. Examples of the latter include the Parkes telescope at 1400 MHz (Petroff et al. 2015a), the ARTEMIS backend and LOFAR array operating at a much lower frequency of 145 MHz (Karastergiou et al. 2015), and the BURST project with the Molonglo Observatory Synthesis Telescope which operates at an intermediate frequency of 843 MHz (Caleb et al. 2016).

When the expected DM contribution from the Galaxy is removed using the Cordes & Lazio (2002) Galactic electron model, none of the FRBs detected to date has an extragalactic DM contribution (DM excess) larger than ∼1550 pc cm^{-3} (Champion et al. 2016). Zheng et al. (2014) have shown that there is a complicated non-linear relationship between the DM contribution from the intergalactic medium (IGM) and redshift. However, as seen in their fig. 1, for small redshifts ($z \lesssim 3$), a linear approximation can be made in which ∼900–1100 pc cm^{-3} of DM is contributed per redshift unit. A DM excess of ∼1550 would then correspond to a redshift of $z \sim 1.5$ assuming that the IGM is the primary source of the dispersion. However, significant local dispersion near the source or contributions from the host galaxy could further boost the measured DM. Thus, if FRBs beyond this redshift range are to be discovered, larger DMs must be searched for burst signals.

We have searched three Parkes radio pulsar surveys to try and detect putative bursts at very large DMs (up to a DM of 5000 pc cm^{-3}). These three surveys were previously searched for FRBs in the single-pulse search analysis done during the original data processing, and in fact, one of the surveys contains the first FRB found, FRB 010724 (Lorimer et al. 2007). One of the other surveys has a known Peryton present (Burke-Spolaor et al. 2011). However, none of the three surveys have yet been searched out to high DMs (>1000 pc cm^{-3}). All three of the surveys targeted sky regions away from the Galactic plane (all beams had Galactic latitudes $|b| > 5°$; see Table 1). This avoids foreground effects from the Galaxy that can negatively affect the detectability of FRBs through increased pulse scattering and sky temperature (Burke-Spolaor & Bannister 2014; Petroff et al. 2014).

Below we describe each of the three surveys we searched and outline our FRB search procedure. We then describe our results and the subsequent constraints on the all-sky rate of FRBs.

2 OVERVIEW OF THE SURVEYS

The three surveys we have analysed were all conducted with the Parkes radio telescope using the 13-beam multibeam receiver (Staveley-Smith et al. 1996). Note that all but two of the FRBs detected and listed to date in the Swinburne FRB Catalogue (Petroff et al. 2016) were detected with this same observing system. Table 1 describes the observing parameters for each of these three surveys, which have a cumulative multibeam on-sky time of 719 h.

The first survey ['Small Magellanic Cloud (SMC)'] was a deep search for pulsars in the Magellanic Clouds. Both the Small (SMC) and Large (LMC) Magellanic Clouds were searched with the same analogue filterbank system as was used in the highly successful Parkes Multibeam Pulsar Survey (Manchester et al. 2001). A total of 22 new pulsars were discovered in this survey during several processing passes through the data (Crawford et al. 2001; Manchester et al. 2006; Ridley et al. 2013). The first FRB ever discovered, FRB 010724 (Lorimer et al. 2007), was also detected in this survey. Prior to the work described here, this survey had only been searched for periodic signals and single pulses out to a maximum DM of 800 pc cm^{-3}. A total of 488 h of on-sky time was recorded in the survey.

The second survey ('EGU') targeted 56 unidentified mid-Galactic latitude gamma-ray sources from the third EGRET catalogue (Hartman et al. 1999). The same observing system was used for this survey as for the SMC survey described above, but with different integration and sampling times (see Table 1). The results of the survey were presented by Crawford et al. (2006). The data were previously searched out to DM = 1000 pc cm^{-3}, and six new pulsars were discovered. One of these was PSR J1614−2230, a binary system with a pulsar mass of $1.97 \pm 0.04\,M_\odot$ (Demorest et al. 2010). A Peryton RFI burst signal was also discovered in this survey (Burke-Spolaor et al. 2011). This survey recorded a total of 135 h of on-sky time.

The third survey ('PLMC') is a new pulsar and transient survey of the LMC which is sensitive to millisecond pulsars in the LMC for the first time. Like the two surveys above, it uses the Parkes telescope and the multibeam receiver, but with the Berkeley–Parkes–Swinburne Recorder (BPSR) digital backend (Keith et al. 2010). This has a fast sampling capability and narrow frequency channels (see Table 1 for details), and 20 per cent of the total survey data has been collected and processed so far (corresponding to 96 h of on-sky time). The initial results from this work were described by Ridley et al. (2013), where three new pulsars were discovered. In this processing, the data were searched for pulsations and single bursts out to DM = 500 pc cm^{-3}, but no new FRBs have yet been detected in this survey.

3 ANALYSIS

In our re-analysis of these surveys, we searched the data for impulsive signals at a much larger range of DMs than previously searched. We searched DMs ranging from 0 to 5000 pc cm^{-3} with a variable DM trial spacing that had a wider spacing at larger DMs. The spacing was chosen so that the smearing introduced from a DM offset would not significantly increase the DM smearing already present within the finite frequency channels. Table 1 lists the number of DM trials used in each survey analysis.

Each de-dispersed time series was searched for signals using a widely used single-pulse detection algorithm in the SIGPROC[2] pulsar analysis package. This algorithm is described in detail by Cordes & McLaughlin (2003) (see also Rane et al. 2016 for a discussion) and uses a boxcar smoothing technique to maintain sensitivity to pulses at a wide range of time-scales. The boxcar filters were produced by averaging adjacent time samples in 10 successive groups of two, yielding boxcar widths ranging from 1 to 1024 time samples (see Table 1 for the sampling times used for the different surveys). The boxcar sample aggregation was successively applied to each de-dispersed time series, with the highest resulting signal-to-noise ratio (S/N) signal from the passes through the data being kept. Only signals with a S/N $\geq$ 5 were recorded. Note that this technique has been shown by Keane & Petroff (2015) to reduce sensitivity to events which are offset from the boxcar centres by as much as a factor of $\sqrt{2}$ (as compared to a convolution of the time series with comparable boxcar filters). This sensitivity reduction was taken into account in our estimate of the all-sky FRB event rate.

A single-pulse diagnostic plot was produced for each beam (see Fig. 1). In this plot, a short, dispersed impulse would appear in the DM versus time plot as a signal at a non-zero DM that is localized in both dimensions. The size of the circles indicates the S/N.

No radio frequency interference (RFI) excision was performed prior to the de-dispersion and pulse search. However, RFI was cleaned in the resulting single-pulse plots. If an RFI signal appeared at a DM of zero (indicating a terrestrial signal), then samples at all DMs corresponding to the time of that event were removed. This technique efficiently removed both non-dispersed broad-band RFI and sporadic narrow-band RFI while maintaining the detectability of dispersed broad-band pulses (see Fig. 1). After cleaning, both the cleaned and uncleaned plots were checked by eye for indications of dispersed pulse events.

4 RESULTS AND DISCUSSION

We discovered no new FRBs in the three surveys we searched out to a DM of 5000 pc cm^{-3}. We did clearly detect both FRB 010724 (Lorimer et al. 2007) in an SMC survey beam and the Peryton interference signal present in several EGU survey beams (Burke-Spolaor et al. 2011). This signal has been identified as a source of RFI (Petroff et al. 2015b), but since it mimics some of the characteristics of FRBs, it is a good test of our single-pulse detection algorithm.

Both of these detections were made blindly (i.e. during the routine analysis of the survey data). These detections are shown in Fig. 1, and these are the only FRB-type signals known to be present in these surveys. Note that, in addition to these two single-burst events, a number of known pulsars were also detected during the processing as single-pulse sources.

We used the null detection of any new FRBs in these three surveys we analysed plus the results from five other Parkes multibeam 1.4 GHz surveys that have been searched for FRBs (see Rane et al. 2016) to determine a new constraint on the all-sky FRB rate. These other large-scale Parkes surveys have all been searched out to high DMs (at least a DM of 3000 pc cm^{-3}; see table 2 of Burke-Spolaor & Bannister 2014).

The five additional surveys we included in our FRB rate estimate are listed below (see also table 2 of Rane et al. 2016 which gives additional details of each survey).

(i) The High Time Resolution Universe South (HTRU-S) high-latitude survey (Champion et al. 2016). A total of 2812 h of on-sky time was recorded in this survey and nine new FRBs were discovered.

[2] http://sigproc.sourceforge.net/

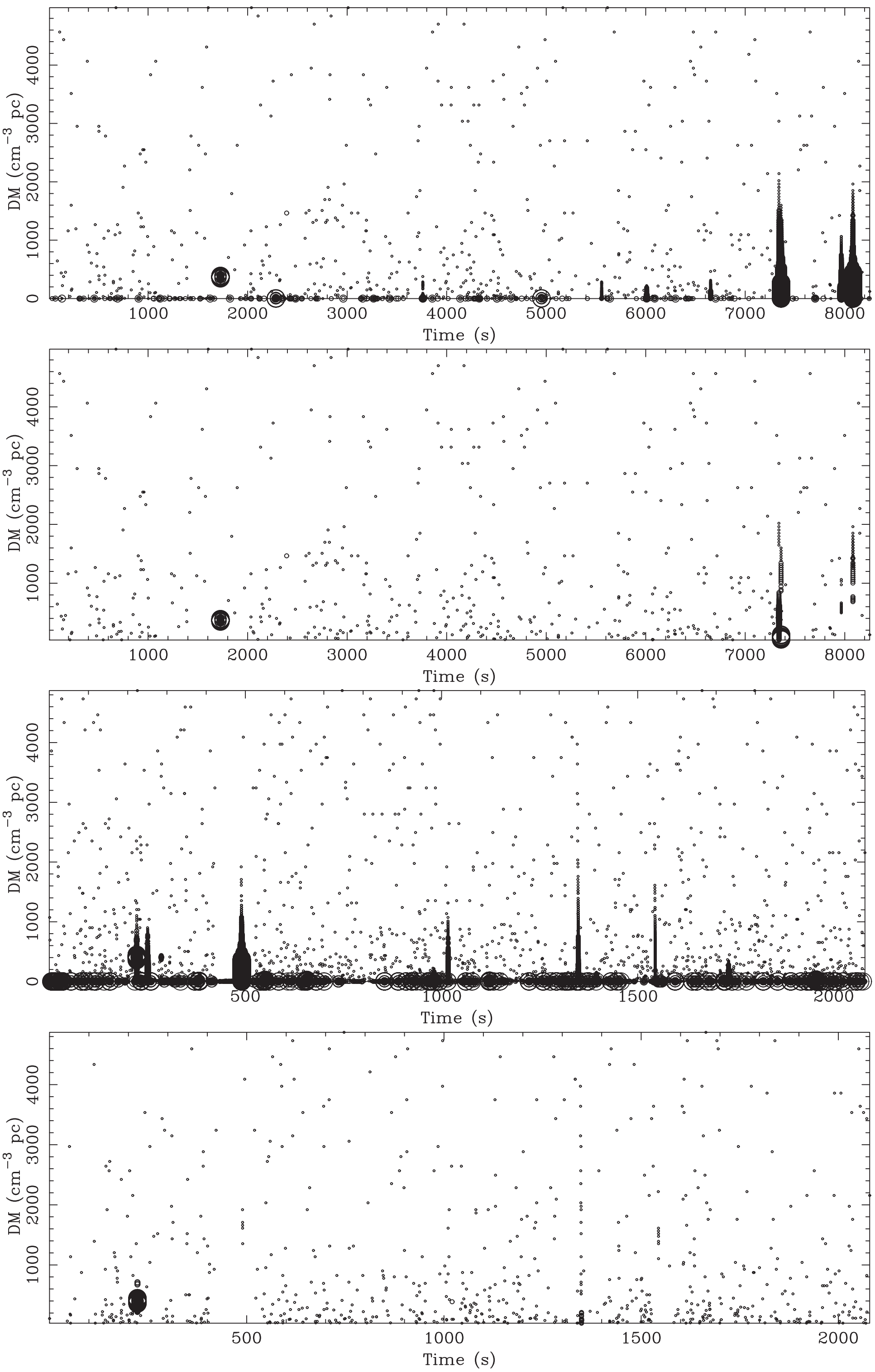

Figure 1. Single-pulse detections of two known burst signals present in the surveys we analysed: FRB 010724 (Lorimer et al. 2007) from the SMC survey (shown in the top two panels), and a Peryton RFI signal (Burke-Spolaor et al. 2011) from the EGU survey (shown in the bottom two panels). Each pair of panels shows DM versus time prior to RFI cleaning (top panel) and after cleaning (bottom panel) for that particular source. The symbol size indicates signal strength. The cleaning process removes undispersed broad-band terrestrial RFI (clustered at DM = 0 throughout the integration) and narrowband RFI (occasional thin vertical signals) while preserving broad-band dispersed signals. Both signals are clearly detected in the diagnostic plots.

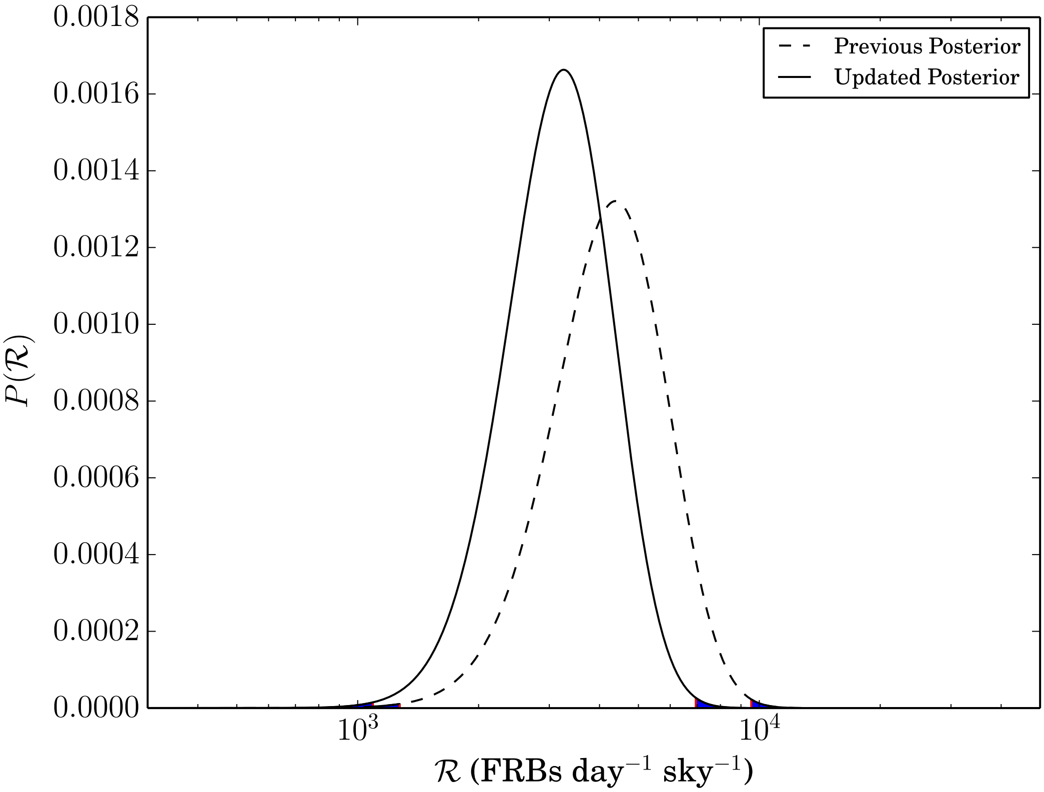

Figure 2. The posterior probability density function of the event rate of Parkes-detectable FRBs, determined from the five Parkes surveys (totalling 7512 h) analysed by Rane et al. (2016) (dashed curve) and from the addition of the three Parkes surveys (totalling 719 h) described in this paper (solid curve). See also table 2 of Rane et al. (2016). All surveys were searched to high DMs (at least 3000 pc cm^{-3}). The rate analysis considered the different single-pulse search processing methods and observing backends used in the different surveys. The resulting new all-sky FRB rate is $R = 3.3^{+3.7}_{-2.2} \times 10^3$ events per day per sky above a fluence limit of 3.8 Jy ms at the 99 per cent confidence level.

(ii) The HTRU-S intermediate-latitude survey (Petroff et al. 2014). A total of 1154 h of on-sky time was recorded. No new FRBs were found.

(iii) The Swinburne Multibeam survey (Burke-Spolaor & Bannister 2014). 925 h total was recorded and one new FRB was discovered.

(iv) The Parkes Multibeam Pulsar Survey (PMPS; Manchester et al. 2001). This survey targeted low Galactic latitudes and had an on-sky integration of 2115 h. One new FRB was detected here.

(v) The Parkes High-Latitude survey (Burgay et al. 2006). 506 h of total on-sky time was recorded with no new FRBs found.

We added the 7512 h of time from the surveys above to the 719 h from our three surveys, and following the method of Rane et al. (2016), we ran a likelihood analysis to determine a statistically likely all-sky rate of detectable FRBs. From this combined survey set, we find a rate of $R = 3.3^{+3.7}_{-2.2} \times 10^3$ events per day per sky above a fluence limit of 3.8 Jy ms at the 99 per cent confidence level. This is an improvement over the Rane et al. (2016) limit of $R = 4.4^{+5.2}_{-3.1} \times 10^3$ events per day above a 4 Jy ms fluence limit (99 per cent confidence). Fig. 2 shows the likelihood function for both the old and new all-sky rates.

Our derived FRB event rate above a uniform fluence threshold combines the results of the rates determined individually from the eight different Parkes surveys, while also accounting for the different single-pulse search processing methods and different telescope backends used in these surveys (see Rane et al. 2016, for further details). Other rate estimates that have been published from Parkes observations have used only a single survey or subset of surveys (e.g. the HTRU-S survey analysed by Keane & Petroff 2015; Champion et al. 2016) which have a smaller total on-sky time than the combined set of surveys that we used. Given the large uncertainties in all of these rates (including ours), they are all compatible with each other. However, our rate is an improvement on the recent Rane et al. (2016) rate estimate since we have included the on-sky time from three more surveys to their analysis and detected no additional FRBs. We note that the PMPS was conducted at low Galactic latitudes ($|b| < 5°$), and Galactic-plane effects may significantly influence detectability of any FRBs present and hence can affect underlying FRB rate estimates.

The inclusion of this information in the future analysis of other Parkes multibeam surveys (such as the complete PLMC survey, of which only 20 per cent has been observed and processed; Ridley et al. 2013) will help further constrain the all-sky FRB rate.

5 CONCLUSIONS

We have analysed three Parkes multibeam surveys for FRBs at a range of DMs extending out to 5000 pc cm^{-3}, a much higher DM limit than what was previously searched in these surveys. We detected one known FRB and one known Peryton interference signal that were present in these surveys, but found no new FRBs. We used the 719 h of multibeam on-sky time from our three surveys and the 7512 h of on-sky time from five other large-scale Parkes multibeam surveys searched out to high DMs (at least 3000 pc cm^{-3}) to improve the constraint on the FRB all-sky rate. We determine a rate of $R = 3.3^{+3.7}_{-2.2} \times 10^3$ events per day per sky above a fluence limit of 3.8 Jy ms at the 99 per cent confidence level. Results from future Parkes surveys will be able to be combined with these results to further constrain the underlying FRB rate.

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