Five new fast radio bursts from the HTRU high-latitude survey at Parkes: first evidence for two-component bursts

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ABSTRACT

The detection of five new fast radio bursts (FRBs) found in the 1.4-GHz High Time Resolution Universe high-latitude survey at Parkes, is presented. The rate implied is $7^{+5}_{-3} \times 10^3$ (95 per cent) FRBs $\mathrm{sky^{-1}\,d^{-1}}$ above a fluence of 0.13 Jy ms for an FRB of 0.128 ms duration to 1.5 Jy ms for 16 ms duration. One of these FRBs has a two-component profile, in which each component is similar to the known population of single component FRBs and the two components are separated by 2.4 ± 0.4 ms. All the FRB components appear to be unresolved following deconvolution with a scattering tail and accounting for intrachannel smearing. The two-component burst, FRB 121002, also has the highest dispersion measure (1629 pc $\mathrm{cm^{-3}}$) of any FRB to-date. Many of the proposed models to explain FRBs use a single high-energy event involving compact objects (such as neutron-star mergers) and therefore cannot easily explain a two-component FRB. Models that are based on extreme versions of flaring, pulsing, or orbital events, however, could produce multiple component profiles. The compatibility of these models and the FRB rate implied by these detections is discussed.

Key words: scattering – surveys – pulsars: general – intergalactic medium.

1 INTRODUCTION

The first detected fast radio burst (FRB), now known as FRB 010724 (named using the last two digits of the year, month, and day), was found in a search for pulsars using a technique to detect bright single pulses using the Parkes radio telescope (Lorimer et al. 2007). The burst followed the frequency–time relation associated with dispersion of light in an ionized plasma precisely but the dispersion measure (DM, the integrated free electron density along the line of sight) was more than eight times that could be accounted for by the Milky Way. The non-repeating nature, short duration, implied extragalactic origin (due to the large DM), and therefore luminosity made it clearly different to known short duration radio transients, such as giant pulses from pulsars and rotating radio transients.

Reprocessing of the Parkes Multibeam Pulsar Survey (Manchester et al. 2001) resulted in the detection of a burst very similar to FRB 010724 (Keane et al. 2011). Again, it precisely followed the dispersion relation and was never seen to repeat but in contrast to the high Galactic latitude of FRB 010724 this burst was only 4° from the Galactic plane. The DM was only 40 per cent above the maximum contribution from the Milky Way expected by the NE2001 model (Cordes & Lazio 2002), and as this and other similar models have large uncertainties on individual lines of sight, a Galactic origin for this burst could not be ruled out (Keane et al. 2012; Bannister & Madsen 2014).

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With only a single bright event, the origin of FRB 010724 proved controversial until the discovery of four FRBs in the High Time Resolution Universe (HTRU) survey (also using the Parkes telescope) provided a first population of these events (Thornton et al. 2013). These additional FRBs allowed a rate estimate of $R_{F\sim 3\,Jy\,ms} = 1.0^{+0.6}_{-0.5} \times 10^4$ sky^{-1} d^{-1} with a confidence limit of 68 per cent. The first FRB found with a telescope other than Parkes came from the Pulsar Arecibo L-band Feed Array survey using different hardware and software (Spitler et al. 2014). Since then, FRB 010125 has been found in archival data that predates the first discovery (Burke-Spolaor & Bannister 2014), FRB 140514 was detected in real time allowing for fast multifrequency follow-up (Petroff et al. 2015a), FRB 131104 was discovered during observations of the Carina Dwarf Spheroidal Galaxy (Ravi, Shannon & Jameson 2015) and FRB 110523 was discovered in a Green Bank hydrogen survey (Masui et al. 2015). Hence, a total of 10 likely extragalactic FRB detections are in the literature, but the physical model explaining them is still unknown. A reprocessing of HTRU survey data taken at mid-Galactic latitudes ($|b| < 15°$, $-120° < l < 30°$) for FRBs resulted in no detections (Petroff et al. 2014). This has been shown to be 99.5 per cent incompatible with the rate quoted in Thornton et al. (2013) and suggests either a non-uniform distribution or that the detectability of FRBs varies as a function of latitude due to latitude-dependent effects of the Galaxy (Macquart & Johnston 2015). However a search of archival data by Rane et al. (2016) determined a lower rate (yet still consistent with other published rates) that assumes a uniform distribution on the sky.

The extremely short duration of the FRBs suggests that the source must be compact and the apparent luminosity requires a coherent, energetic process ($>10^{31}$ J; Lorimer et al. 2007; Thornton et al. 2013). There are many proposed origins of FRBs including evaporating black holes (Rees 1977), hyperflares from soft gamma-ray repeaters (SGRs; Popov & Postnov 2010), merging white dwarfs (Kashiyama, Ioka & Mészáros 2013) or neutron stars (Hansen & Lyutikov 2001), collapsing supra-massive stars (Falcke & Rezzolla 2014), supergiant pulses from pulsars (Cordes & Wasserman 2016), Alfvén waves from bodies orbiting a pulsar (Mottez & Zarka 2014), and even cosmic string collisions (Cai et al. 2012).

In this Letter, we will describe the observations and analysis in Section 2 before describing five new FRBs in Section 3. Interestingly, for the first time, we have detected two pulses in one burst, FRB 121002. The impact of these discoveries on the calculated rates of FRBs, and in particular the implication of FRB 121002 for proposed models of their origin is discussed in Section 4.

2 OBSERVATIONS AND ANALYSIS

The HTRU survey is an all-sky survey for pulsars and fast transient sources using the Parkes 64-m radio telescope in the Southern hemisphere (Keith et al. 2010) and the Effelsberg 100-m telescope in the Northern (Barr et al. 2013). As the pulsar population and propagation effects due to the interstellar medium depend on Galactic latitude, the survey was split into three Galactic latitudes ranges. The data presented here come from the Southern high-latitude part of the survey ($\delta < +10°$) targeting fast-spinning pulsars and FRBs; the pulsar search results will be presented elsewhere. This part of the survey comprised 33 500 pointings of the 13-beam receiver, each for 270 s with a bandwidth of 340 MHz centred at 1.3 GHz. As this is a blind search for transient events, it is useful to consider the product of the field-of-view and total observing time, in this case 1549 deg^2 h calculated to the half-power beamwidths. A full description of the survey can be found in Keith et al. (2010).

The publication from Thornton et al. (2013) was based on processing a subset of this same survey area. At the time of that publication, 316 deg^2 h had been processed with 1400 DM trials up to a maximum of 2000 pc cm^{-3}. The DM trials were spaced such that the signal-to-noise ratio (S/N) of a burst occurring between trials was reduced less than 1.25. A low-DM cut of 100 pc cm^{-3} and a minimum S/N of 9 was applied before human inspection of all candidates. Multibeam rejection was also used to reject interference, any candidate appearing in more than nine beams was removed. This resulted in the discovery of four FRBs.

Following that analysis, a new processing pipeline known as HEIMDALL[1] was developed. Using graphics processing unit (GPU) technology, this pipeline is considerably quicker than the previous processing while allowing a larger range of parameters to be searched (Keane & Petroff 2015). This pipeline was used to process the data presented here including, for completeness, the 316 deg^2 h in Thornton et al. (2013). The data were searched for single pulses matching a number of criteria attributed to FRBs. The search for single pulses occurs in the three dimensions of time, DM, and pulse width typical to many single pulse searches. The number of false positives quickly becomes prohibitive as the search width increases so the data were searched over widths ranging from 0.128 to 16 ms, and over 1749 DM trials from 0 to 5000 pc cm^{-3}.

Individual beams of data from the receiver were searched with HEIMDALL and then run through a coincidence algorithm to identify and cluster events occurring in more than one beam. The candidates were then concatenated into a single file for the pointing. Pulses matching the following criteria were flagged as FRB candidates:

$$S/N \geq 10 \qquad (1a)$$

$$\Delta t \leq 2^8 \times 64 \; \mu s = 16.3 \; ms \qquad (1b)$$

$$DM/DM_{Galaxy} > 0.9 \qquad (1c)$$

$$N_{beams} \leq 4, \qquad (1d)$$

where Δt is the pulse width, DM_{Galaxy} is the modelled Galactic DM contribution along the line of sight from NE2001 (Cordes & Lazio 2002), and N_{beams} is the number of beams of the multibeam receiver in which the signal is detected. The thresholds for this search are identical to those from Petroff et al. (2014) to maintain consistency in the FRB search across the intermediate and high-latitude components of the HTRU survey.

3 RESULTS

The entire 1549 deg^2 h of the Southern HTRU high-latitude survey was processed using the HEIMDALL software, $\sim$7 per cent were unusable due to interference or corrupted files resulting in 1441 deg^2 h of processed data. As these included data previously analysed by Thornton et al. (2013), the re-detection of the previously known FRBs served as a validation of our pipelines. Indeed, those FRBs were detected with S/Ns similar to the original processing and one new detection, FRB 110214, was made (to be presented elsewhere). The processing of the additional 1233 deg^2 h of observations in the high-latitude survey resulted in the detection of five FRBs. The only

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[1] http://sourceforge.net/projects/heimdall-astro

Table 1. The five FRBs presented in this work. The time is the peak arrival time at the centre of the band. Sky positions are taken as the location of beam centre with radial errors of 7.5 arcmin (the full width at half-maximum). DM_{Gal} is taken from the NE2001 model. t_{DM} is the intrachannel smearing time at the band centre. The scattering time τ has been scaled to a reference frequency of 1 GHz. W_{Int} is the intrinsic width of the pulse before intrachannel smearing and scattering broaden the pulse. In the case of FRB 121002 the scattering time and W_{Int} measurement applies to both components individually. The fluences are calculated using the radiometer equation assuming the FRB was at the beam centre and so should be considered to be lower limits. The values in parenthesises indicates the 1σ uncertainty in the last digit. The last column gives the relative likelihood of a double (Gaussian) component model versus a single (Gaussian) component model with scattering, as derived from the AIC corrected for finite sample size.

Name	Date and time	Position		S/N	DM	DM_{Gal}	t_{DM}	τ	W_{Int}	Fluence	P
		RA	Dec.								
	(UTC)	$(^{h}{:}^{m}{:}^{s})$	$(^{\circ}{:}'{:}'')$		(pc cm^{-3})		(ms)	(ms)	(ms)	(Jy ms)	
FRB 090625	2009-06-25 21:53:52.85	03:07:47	−29:55:36	28	899.6(1)	32	1.3	3.7(7)	<1.9	>2.2	0.85
FRB 121002	2012-10-02 13:09:18.50	18:14:47	−85:11:53	16	1629.18(2)	74	2.4	6.7(7)	<0.3	>2.3	1E9
FRB 130626	2013-06-26 14:56:00.06	16:27:06	−07:27:48	20	952.4(1)	67	1.4	2.9(7)	<0.12	>1.5	0.14
FRB 130628	2013-06-28 03:58:00.02	09:03:02	+03:26:16	29	469.88(1)	53	0.7	1.24(7)	<0.05	>1.2	0.63
FRB 130729	2013-07-29 09:01:52.64	13:41:21	−05:59:43	14	861(2)	31	1.3	23(2)	<4	>3.5	25.0

mulitiple-beam detection was for FRB 090625 which was detected in a second beam.

Following a detection using HEIMDALL, for each FRB the full bandwidth was divided into a smaller number of (typically eight) sub-bands. A Gaussian template was convolved with a scattering tail (a one-sided exponential) using a characteristic scattering time τ. The scattering time for each sub-band was related to the centre frequency of the observation by $\tau = \tau_{Cen}(\nu/\nu_{Cen})^{-4}$; after fitting the scattering time at the reference frequency of 1 GHz was calculated using the same relation. The template was a Gaussian whose width was varied to minimize the χ^2-value. For FRB 121002 a double Gaussian was required. In all of the FRBs (including the individual components of FRB 121002), the resulting widths are consistent with smearing due to intrachannel dispersion, i.e. the pulses are unresolved. Using the arrival time of the burst at reference frequency ν_0, the arrival time at a frequency ν was scaled according to a cold plasma dispersion law $t = t_0 + k \times DM/\nu^2$. The parameters τ, DM, and t_0 were determined in a least-squares fit using the SIMPLEX and MIGRAD algorithms from CERN's MINUIT package.[2] Uncertainties were derived using the MINUIT algorithm to explore the error matrix, it also attempts to account for correlations between parameters. A baseline and amplitude of the scattered pulse of each sub-band were also fitted as free parameters. The results are summarized in Table 1.

To confirm that the apparent double peaks seen in FRB 121002 are significant, the Akaike Information Criterion (AIC; e.g. Burnham & Anderson 2002) was used to compare using a single and double Gaussian template for the FRB when dedispersed and summed across the detected bandwidth. The resulting χ^2 values of the fits and numbers of parameters in the models were evaluated using the AIC (corrected for finite sample size) and the ratio gave the relative likelihood. The double Gaussian model was more likely than the single by more than nine orders of magnitude for FRB 121002. This test was applied to the other FRBs in this Letter. For FRB 090625, there was no significant difference between single and double Gaussian models and for all other FRBs the single Gaussian model was clearly preferred.

FRB 130729 was only detected in the lower half of the observing band, and was most strongly detected at the lowest frequencies. This could be evidence of a steep spectral index but is equally consistent with the FRB coming from the edge of the beam where the receiver's sensitivity to higher frequencies diminishes quickly (Staveley-Smith et al. 1996). The lower bandwidth makes the DM

determination less precise and the detection weaker. While it is possible that this is terrestrial radio interference, the lack of a similar detection in other beams and DM suggests that it is of astrophysical origin. Although it appears that there may be a double-peak structure in this FRB, it is not statistically preferred.

The five FRBs are shown in Fig. 1 and detailed in Table 1. In each case the contribution to the DM from the Milky Way is estimated using the maximum value from the NE2001 model for the given line of sight. All the FRBs presented here show a very significant DM in excess of the Milky Way contribution. FRB 121002 has the highest DM of any FRB thus far detected at 1629 pc cm^{-3}. If we assume that FRBs originate in an external galaxy then some of the DM will come from this host galaxy, this contribution is obviously uncertain. The intergalactic medium DM contribution is calculated using the models of Ioka (2003) and Inoue (2004), from which we can also estimate a corresponding redshift (Thornton et al. 2013). This gives FRB 121002 an upper limit on redshift of $z < 1.3$ by giving a host contribution of 0 pc cm^{-3} and acknowledging that the host could contribute anything above this value depending on progenitor location and orientation of the host galaxy.
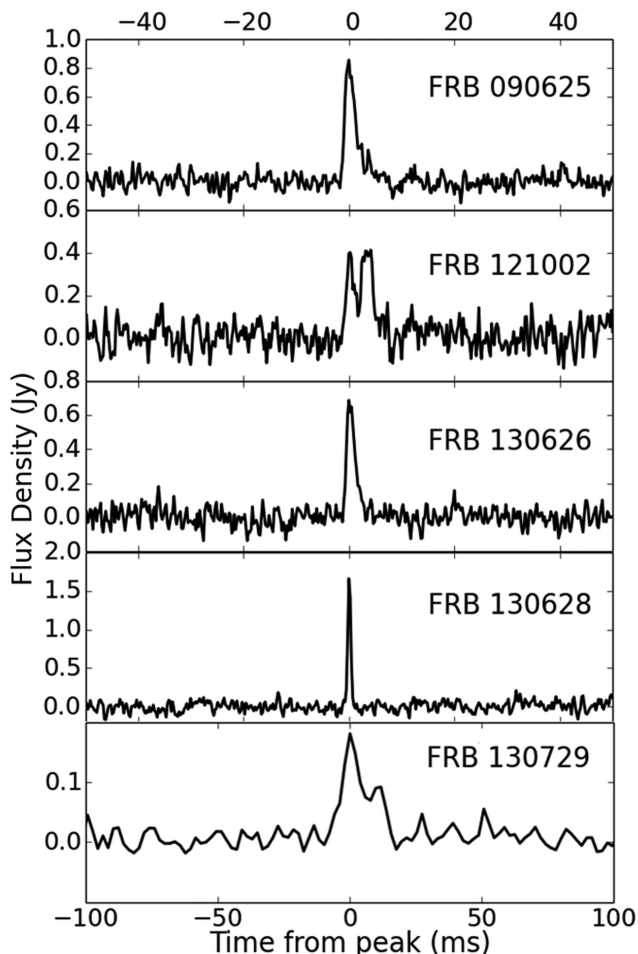
Both components of FRB 121002 can be fitted with the same DM, width, and scattering time. They have a separation of 2.4 ± 0.4 ms, and the relative amplitude of the first component to the second component (before scattering) is 0.91 ± 0.2. Assuming these bursts originate beyond the Milky Way, there will be a significant redshift that will have stretched the component separation between emission and detection. The upper limit for the redshift of FRB 121002 is 1.3 which results in an emission separation of 1.0 ± 0.2 ms once the factor of $1 + z$ has been applied. The overall width of FRB 121002 is similar to those of FRBs 010724, 110220, and 130729 which suggests that some FRBs may have multiple components that are indistinguishable following scattering and intrachannel smearing.

4 DISCUSSION AND CONCLUSIONS

With the complete sample of FRBs from the high-latitude survey, we are able to provide an updated FRB rate with the largest sample of FRBs to date. The HTRU high-latitude survey consisted of 1441 deg^2 h of observations in which 10 FRBs were detected. Using the total time on sky and square degrees observed an all-sky rate can be calculated assuming an isotropic distribution as

$$10\ \text{FRBs} \times \frac{24\ \text{h d}^{-1} \times 41253\ \text{deg}^2\ \text{sky}^{-1}}{1441\ \text{deg}^2\ \text{h}}. \qquad (2)$$

[2] http://www.cern.ch/minuit

Figure 1. The five FRBs presented in this work. The data have been smoothed from an initial sampling of 0.24 ms (1.9 ms for FRB 130729) using a Gaussian filter of full width at half-maximum 0.33 ms (2.6 ms for FRB 130729). The flux density scale is calculated using the radiometer equation and assuming the FRB was at the beam centre, therefore these flux densities should be considered to be lower limits. Note that the horizontal scale for the upper four panels is at the top of the figure, while the scale for the bottom panel is below.

This results in a rate of $7^{+5}_{-3} \times 10^3$ (95 per cent confidence interval) FRBs sky^{-1} d^{-1} above a fluence of 0.13 Jy ms for an FRB of 0.128 ms duration to 1.5 Jy ms for 16 ms duration. The confidence intervals were obtained using the Poissonian upper and lower error estimates for the number of detections (from Gehrels 1986). This is consistent with those previously reported in Thornton et al. (2013), Spitler et al. (2014), and Rane et al. (2016) within the quoted uncertainties. It should be noted that this rate is specific to the observing setup described in this Letter as this setup is not fluence-complete to the same level as other surveys, thus it is only directly comparable to Thornton et al. (2013). The fluence-complete rate, above a fluence of ∼2 Jy ms (Keane & Petroff 2015), is $2.1^{+3.2}_{-1.5} \times 10^3$ (95 per cent confidence interval) FRBs sky^{-1} d^{-1}.

For the first time an FRB has been observed that clearly shows multiple components. Falcke & Rezzolla (2014) proposed that the collapse of a supramassive star into a black hole could be the origin of FRBs. This model, building on the work in Dionysopoulou et al. (2013), does predict structure within the pulse profile, specifically in the form of a leading precursor, main pulse, and ringdown occurring within 1 ms for a non-rotating star, however the separation

of the components will be dependent on the rotation speed of the star, with more rapidly rotating stars having more widely separated components. Further modelling will be required to see if this model can account for the separation observed.

One of the models favoured by some authors relates FRBs to the giant flares from SGRs (e.g. Popov & Postnov 2010; Thornton et al. 2013; Kulkarni et al. 2014). The initial gamma-ray burst usually lasts just a fraction of a second, and is then followed by hard X-ray emission with power modulated at what is thought to be the spin period of the underlying neutron star (e.g. Hurley et al. 2005; Palmer et al. 2005). It is possible that the burst in gamma rays could correspond to the initial peak. However the origin of the second peak would require structure within a single pulse or that the two bursts are two rotations of the SGR. In the latter case the spin period would be much shorter than the currently known population of SGRs. If the radio emission displayed the same dramatic decrease in flux seen in the gamma-ray emission, then no subsequent individual pulses would be expected to be seen for the known bursts. A search for periodic radio emission shortly after the burst was unsuccessful, see chapter 6 of Thornton (2013) for details and a discussion of the energetics.

Another model that may be able to explain a double-peaked profile was presented by Cordes & Wasserman (2016). They suggest that the giant pulse behaviour of some pulsars (most notably the Crab pulsar) may extend to higher fluences. Giant pulses are generally defined as pulses that are of the order of 10 times stronger than the average fluence energy (Knight 2007). Giant pulses from the Crab pulsar have been seen to exceed 2 MJy for less than 4 ns (Hankins & Eilek 2007). They are often extremely narrow (e.g. 0.5 μs; Bhat, Tingay & Knight 2008) and have a power-law pulse energy distribution and in some cases are seen to show structured pulses (e.g. Karuppusamy, Stappers & van Straten 2010). Giant pulses are also seen from millisecond pulsars, and the separation between the pulses could therefore represent the rotation period. Cordes & Wasserman (2016) suggest that if this distribution continues to higher fluences then, although these 'supergiant' pulses would be extremely rare, the volume of the Universe where they could be observed, and so the number of potential sources, makes them a possible origin of FRBs. They also suggest that for higher redshifts gravitational microlensing would play a role. In the case of the double-peaked FRB two supergiant pulses at different phases of rotation of a slowly rotating pulsar, or two consecutive supergiant pulses of a fast-rotating pulsar could account for the structure observed.

Mottez & Zarka (2014) have suggested that a body in orbit around a pulsar could produce highly focused beams of radio emission coming from the magnetic wake of this body as it passes through the pulsar wind. They predict that such bodies would have a system of Alfvén wings which could produce radio emission that lasts for several seconds and is composed of four pulses each with millisecond-durations. Depending upon the line of sight several of these pulses may be observed. While it is not clear what the expected rate would be, this model does predict repetition of these pulses at the orbital period of the companion. With the orbital period of the unknown companion unconstrained this cannot be ruled out. Petroff et al. (2015b) have ruled out periodic repeating sources with periods $P \le 8.6$ h and sources with periods $8.6 < P < 21$ h at the 90 per cent confidence level.

Recently Mingarelli, Levin & Lazio (2015) conjectured that radio emission could result from the interaction of a black hole with the magnetic field of a merging neutron star. The authors state that coalescence rates of such systems is too low to explain observed

FRB population but could be responsible for a sub-population and are expected to have a double-peak and precursor pulse. The amplitude ratio of the precursor and peaks of the main pulse, and the separation of these features is dependent on the initial conditions of the system. The separation and amplitude ratio of the components of the main pulse are of the same scale as the simple model presented. While there is no evidence for a precursor pulse in any of the FRBs presented here it could simply be sufficiently weak as to not be detected.

The double peaked FRB 121002 poses significant challenges to many of the models of FRB emission. However, the model of 'supergiant' pulses and the model of hyperflares could both account for this structure. The rates expected by these models is highly uncertain and cannot at present be used as a discriminator. Both the models of supramassive star collapse and black hole neutron-star merger expect structure in the burst but the details of this structure are dependent on the initial conditions of the system and cannot at present be used as a discriminator.

PUBLIC DATA RELEASE

The data for the five FRBs presented here are publicly available through the Swinburne gSTAR Data Sharing Cluster.[3]

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