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Fast Radio Transients: From Pulsars to Fast Radio Bursts

Invited talk

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Abstract. The radio sky is full of transients, their time-scales ranging from nanoseconds to decades. Recent developments in technology sensitivity and computing capabilities have opened up the short end of that range, and are revealing a plethora of new phenomenologies. Studies of radio transients were previously restricted to analyses of archived data, but are now including real-time analyses. We focus here on Fast Radio Bursts, discuss and compare the properties of the population, and describe what is to date the only known repeating Fast Radio Burst and its host galaxy. We also review what will be possible with the new instrumentation coming online.

Keywords. Stars: neutron, black hole physics, telescopes

1. Introduction

The radio sky is a dynamic place. It includes emission from objects such as ultra-high-energy particles, the Sun, flare stars, brown dwarfs, planets, supernovæ, neutron stars in many guises, gravitational wave sources, X-ray binaries and gamma-ray bursts. Here we concentrate on the growing discoveries of Fast Radio Bursts (FRBs).

2. Fast Radio Bursts

FRB research commenced with the discovery of the bright radio transient known as the Lorimer burst (Lorimer *et al.* 2007). It was confirmed as belonging to a population by the discovery of four more by Thornton *et al.* (2013). The bursts last for just a few milliseconds and their fluxes (0.2–150 Jy) indicate a very high brightness temperature ($>10^{33}$ K), which in turn implies that the emission mechanism is coherent. The pulses show a characteristic time-delay that depends quadratically on frequency, indicating that the radio emission has been dispersed by a population of free electrons. However, the number of free electrons which these time delays suggest is much larger than would be expected from our Galaxy along the lines of sight to the bursts. The inference is that they must be at large distances, in some cases up to $z = 2$ (Bhandari *et al.* 2018).

2.1. *Growing population*

The number of FRBs that have been discovered is constantly, and presently rapidly, expanding. Table 1 presents the current number of FRBs that has been published, plus others from private communications. An up-to-date overview of the FRB population can be obtained from FRBcat (http://frbcat.org/; Petroff *et al.* 2016).

Figure 1 shows the distribution of the published FRBs compared to the YMW16 Galactic model of dispersion measure (Yao *et al.* 2017). The uneven nature of the

Table 1. Known population of FRBs. Numbers in parentheses: unpublished announcements.

Telescope	FRBs	Telescope	FRBs
Arecibo	1	Parkes	17 (5)
ASKAP	1 (9)	UTMOST	5
GBT	1		

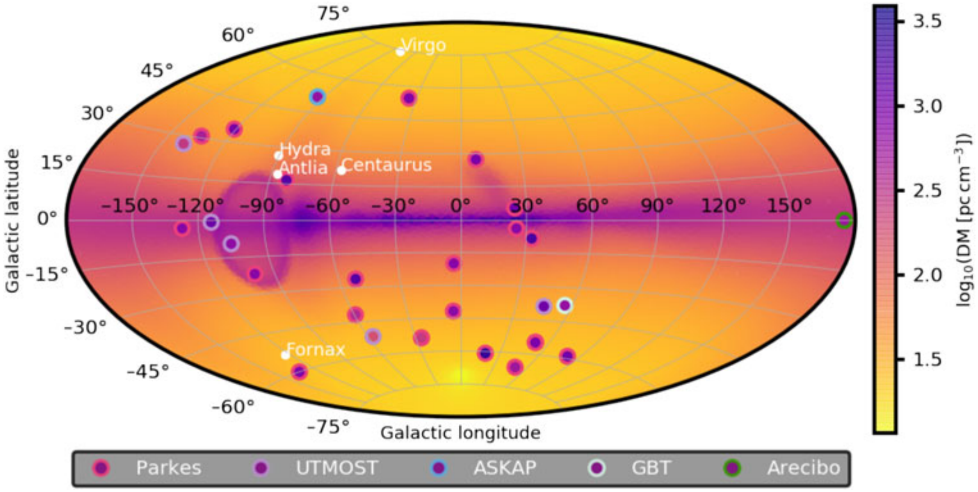

Figure 1. The distribution of published FRBs superimposed on the YMW16 Galactic model of dispersion measure. The colour scale indicates the dispersion measure along the line of sight and for the bursts. The key shows the telescopes with which they were detected.

distribution simply reflects the fact that, to date, the telescopes that have the best combination of sensitivity and field of view for detecting FRBs are located in the southern hemisphere.

The growing sample of FRBs, increased through the reprocessing of all-sky surveys (especially those with significant observing time at low Galactic latitudes), enabled Petroff *et al.* (2014) to study the distribution of FRBs across the sky. By taking into account selection effects such as enhanced sky temperature, increased dispersion-measure smearing and excess scattering at low Galactic latitudes, they found (with 99% confidence) that the FRB distribution was non-isotropic. A similar conclusion was reached by Burke-Spolaor & Bannister (2014). Macquart & Johnston (2015) concluded that the non-isotropy could be due to Galactic diffractive interstellar scintillation. A subsequent study by Vander Wiel *et al.* (2016), based on 13 FRBs at high Galactic latitude, found evidence ($p = 5 \times 10^{-5}$) of a higher rate relative to a single FRB detected at a low Galactic latitude. More recently Bhandari *et al.* (2018) used 15 bursts detected with the Parkes telescope to show that the latitude dependence of the FRB sky rate has reduced significance ($< 2\sigma$).

2.2. *The repeating FRB*

FRB 121102 was the first, and so far the only, FRB discovered with the Arecibo telescope (Spitler *et al.* 2014). It was discovered during the PALFA pulsar survey; it is located in the Galactic anticentre ($l=175$, $b=0.223$) and has a dispersion measure (DM) of $557.4 \pm 2.0\,\mathrm{pc\,cm^{-3}}$, which is about three times greater than the maximum DM predicted for that sightline of $188\,\mathrm{pc\,cm^{-3}}$. The remaining delay, allowing for a host contribution to

Table 2. Published number of hours spent following up some FRBs

FRB	Hours of Follow Up	Reference
FRB 010724 (Lorimer Burst)	250	see Rane & Lorimer (2017)
FRB 110220	>50	see Rane & Lorimer (2017)
FRB 131104	170	Shannon & Ravi (2016)
FRB 140514	>16	Petroff *et al.* (2015)
FRB 150610	10	Bhandari *et al.* (2018)
FRB 150807	215	Ravi *et al.* (2016)
FRB 151206	22.3	Bhandari *et al.* (2018)
FRB 151230	54.9	Bhandari *et al.* (2018)
FRB 160102	15.9	Bhandari *et al.* (2018)

the observed dispersion delay, suggests that it is located at a model-dependent redshift of $z = 0.26$. The radio flux-density spectrum appeared to be highly inverted, suggesting that the source might have been detected in a side-lobe.

Subsequent monitoring of the source showed that, unlike all other FRBs to date (Spitler *et al.* 2016), FRB 121102 repeats. So far more than 100 pulses have been detected (e.g. Scholz *et al.* 2016). Those repeats are only detected rarely, and appear to be emitted in “clumps”. When the source is emitting mode multiple bursts are detected, but subsequently the source may not be detected for long periods of time. Bursts have been detected at frequencies from 1.4 to 8 GHz. The pulse shapes are highly variable, and multiple components are occasionally seen. The spectra show a range of spectral slopes that are sometimes quite narrow-band; however, all pulses are detected at consistent dispersion measures. To date, no underlying periodicity has been seen; the smallest measured separation between bursts is just 34 ms (Hardy *et al.* 2015).

The repeating nature of FRB 121102 enabled it to be localized by using a fast imaging technique on the VLA (Chatterjee *et al.* 2017). The measurement of its position was improved further by using the European VLBI network (Marcote *et al.* 2017) and e-MERLIN. Its location is consistent with a persistent radio source, and enabled the host to be identified as a disturbed dwarf galaxy of about 7 kpc in size at a redshift of 0.19 (Tendulkar *et al.* 2017; Bassa *et al.* 2017). It is offset from the centre of its host galaxy by ∼200 pc, at a position corresponding to a star-formation region of radius 700 pc.

Subsequent to the present review, the rotation measure of FRB 121102 has been measured (Michilli *et al.* 2018); it was shown to be extremely large and possibly variable, indicating an extreme and changing magneto-ionic environment. Fine structure was also seen in the pulses, suggesting a neutron-star origin. The conclusion was that it might be near an intermediate-mass black hole, or buried in a dense nebula or supernova remnant.

Two other FRBs may have associated hosts that have been identified: FRB 150418 (Keane *et al.* 2016) and FRB 131104 (Ravi & Shannon 2015). However, they rely on the identification of variable sources that may (Johnston *et al.* 2017) or may not (Williams & Berger 2016) be associated, and can only be confirmed once more hosts are identified.

2.3. *Are there other repeaters?*

Despite tens to hundreds of hours of follow-up observations of some FRBs, FRB 121102 remains the only known repeater. That is not expected if the other FRBs follow a relationship similar to that of FRB 121102 concerning the number of bursts and burst–flux density, though since FRB 121102 is known to emit its bursts in clumps the time intervals between such clumps in other sources could be variable. Table 2 summarizes the number of hours spent following up some of the FRBs.

2.4. *FRB Rates*

The discovery of the Lorimer burst highlighted the fact that FRBs are common, suggesting that there are 225 $\mathrm{sky}^{-1}\,\mathrm{day}^{-1}$ at a fluence of ∼150 Jy ms. From the four bursts which they detected Thornton *et al.* (2013) showed that, at a fluence of 3 Jy ms, there should be 10000^{+6000}_{-5000} $\mathrm{sky}^{-1}\,\mathrm{day}^{-1}$. Using an expanded data set, Champion *et al.* 2016 deduced a rate of 6000^{+4000}_{-3000} $\mathrm{sky}^{-1}\,\mathrm{day}^{-1}$ above a fluence of 0.13−5.9 Jy ms. The bright burst detected with ASKAP (Bannister *et al.* 2017) confirms the existence of a population of ultra-bright FRBs ($>$ 20 Jy ms). The non-detections of bursts with the VLA (Law *et al.* 2015) and by projects like ALFABURST (Foster *et al.* 2018) and V-FASTR (Wayth *et al.* 2011) are broadly consistent with those rates.

However, all these experiments use frequencies of 1.4 GHz or higher. The bursts detected with UTMOST (Caleb *et al.* 2017) at 843 MHz corresponded to a rate of 78 $\mathrm{sky}^{-1}\,\mathrm{day}^{-1}$ above a fluence of 11 Jy ms. Along with the discovery of a single FRB with the GBT (Masui *et al.* 2015), those are the only FRBs detected below 1 GHz. The lack of detections by very low-frequency surveys (∼150 MHz) with LOFAR (Karastergiou *et al.* 2015), the MWA (Tingay *et al.* 2015) or the GBNCC (∼350 MHz) suggests that the spectral indices of bursts are flat (or that they are not broad-band). It is clear that larger samples of FRBs are needed over a wide range of frequencies in order to understand better their emission properties.

3. Telescopes and Instrumentation

The success of the multi-beam receivers in increasing survey speeds on single-dish telescopes such as Parkes, Arecibo and Effelsberg have become important in the search for fast radio transients, and in particular for FRBs. The latest example is the 19-beam system being deployed on the largest single dish in the world (FAST). To enable the focal region of these dishes to be sampled more completely, phased array feeds are being developed and deployed on many dishes, including the cooled system for the GBT. It is not just the single dishes that are using this method; the WSRT has recently fitted the APERTIF phased-array feed system on most of its telescopes. Improvements are also being made to other existing telescopes, such as improved wider-band receivers for the GMRT and the addition of a commensal transient detection system for e-MERLIN, called LOFT-e. A few of the new telescopes and projects that have recently joined, or are about to join, the search for fast radio transients are mentioned below.

3.1. *CHIME*

The CHIME telescope is a series of four 100×20-m semi-cylinders fitted with 1024 receivers operating in the frequency range 400–800 MHz. It will use an FFT beam-former to produce 1024 beams on the sky covering up to 250 square degrees. This large field of view and high sensitivity will enable it to detect hundreds or thousands of FRBs. The shape of the beams will restrict the localization of the FRBs to tens of arcminutes.

3.2. *UTMOST*

UTMOST is a refurbishment of the MOST telescope (collecting area of 18,000 m^2). It has 7744 ring antennæ operating at 843 MHz with a 31.25 MHz bandwidth and a field of view of 8 square degrees tiled out with 352 fan beams. As indicated in Table 1, UTMOST has already detected successfully a number of FRBs. When the beam locations are chosen appropriately, the localization precision can be constrained to ∼60 square arcminutes.

3.3. *Fly's Eye searches*

Interferometers with many small dishes and large fields of view are ideal for probing the bright end of the FRB luminosity function. It is especially true when used in a 'Fly's Eye' approach, in which each dish is pointed to a different location of the sky. Examples include (a) the ASKAP telescope (which has the very large field-of-view per dish of 30 square degrees); when employing a phased array feed, it could detect the FRBs indicated in Table 1. The ASKAP bursts have interesting spectra. At present the localization of the FBRs is restricted to $\sim$64 square arcminutes, and (b) TRAPUM, a Large Survey Project on the MeerKAT telescope. The hope is to use the 64 dishes of MeerKAT in the future to carry out a Fly's Eye search as well. It will be able to see about 51 square degrees of sky at excellent sensitivity, and the expectation is that it will be able to find roughly one burst for every day on the sky. Some of them may be as bright as the Lorimer burst.

3.4. *MeerTRAP*

MeerTRAP will also use the MeerKAT telescope but in a commensal mode, and will piggy-back on the other MeerKAT Large Survey Projects to search for all types of fast radio transients, including pulsars and FRBs. It will use a combination of coherent and incoherent beams to probe a range of different FRB luminosities. The set-up will include a transient buffer to capture the complex channel data from the 64 MeerKAT dishes; if a burst is detected, the transient buffer will be emptied and an image formed from all the dishes, enabling the localization of the burst to be determined to a few arcseconds (or better). Precise localizations will enable us to identify the host galaxies, and even the regions in those galaxies where the events occurred. In particular, the detections do not rely on the source repeating, nor on any associated emission. MeerTRAP is also working with the MeerLICHT optical telescope, which will be tracking the observing location of MeerKAT with a matching field of view. That should enable us, in effect, to 'look back in time' to see if there was any prompt optical emission, to learn immediately if there is post-burst optical emission, and potentially to identify directly the host galaxy. Over the lifetime of the project MeerTRAP expects to be able to detect, and locate precisely, about 200 FRBs. It will also spend considerable time on some portions of the sky, and so has the potential to probe a range of possible repeat time-scales for FRBs.

3.5. *Square Kilometre Array*

The Square Kilometre Array (SKA) will be an excellent instrument for detecting fast radio transients. SKA1-MID will consist of dishes working at frequencies from a few hundred MHz all the way up to about 15 GHz. It will have a beam-formed mode with 1500 beams which will have excellent sensitivity, and (depending on how it is ultimately used) it could detect at least a few FRBs every day. Such detections, when combined with the transient buffers, would constitute an excellent data set of well-localized bursts. The large number of elements, and the possibilities for sub-arraying, will also enable experiments like Fly's Eye to probe different parts of the luminosity distribution. The exceptional sensitivity and large field of view of SKA1-LOW will ensure that the prospects for detecting radio transients such as pulsars and flare stars with it are very strong. The lack of detections to date below 800 MHz, as discussed above, makes it less clear how effective it will be for detecting FRBs. At the very least it will constrain the spectral properties. Simultaneous experiments with SKA1-MID may provide the best initial determination of its potential.

4. Where Do We Go From Here?

FRB research requires increased numbers of detections. A larger population will support answers to questions such as: What is the distribution of FRBs on the sky? How affected are they by the local interstellar medium? What is their luminosity distribution? Are they standard candles? Is there only a single source population? What are their spectral properties? We also require more rapid responses to bursts in order to follow up at other wavelengths, determine the host location and even the region within the host. We could also derive independent distance estimates, and provide more information to help determine the progenitors. To pursue studies of the intergalactic medium we need large numbers of well-localized objects with precise distances. We could then study the missing baryons, and potentially (if detections are at sufficiently high redshifts) the ionization properties and epochs in the Universe and perhaps even cosmological parameters.

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