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P. Di Matteo, O. Creevey, A. Crida, G. Kordopatis, J. Malzac, J.-B. Marquette, M. N'Diaye, O. Venot (eds)

A DECADE OF FAST RADIO BURST OBSERVATIONS

L. Guillemot[1, 2]

Abstract. Fast Radio Bursts (FRBs) are extremely short and highly-dispersed bursts of radio emission, likely of extragalactic origin. The first FRB was discovered in 2007 in a 1.4 GHz observation conducted with the Parkes radio telescope in Australia. Since then, several tens of FRBs have been observed, over a wide range of radio frequencies. While most known FRBs have never been detected again, a few sources, dubbed "repeaters", are regularly re-detected with consistent emission properties. A little more than a decade since the first FRB detection was reported (that of the so-called "Lorimer burst"), much is still to be learned about the precise origin of these events and the underlying phenomenology. In this talk I presented an overview of FRB observations since their discovery, and of their main properties.

Keywords: Fast Radio Bursts, radio astronomy, transient phenomena

1 The discovery of fast radio bursts

Recognizing that, at the time, the radio sky was 'relatively unexplored for transient signals', McLaughlin et al. (2006) conducted searches for isolated bursts of radio emission in archival data taken with the Parkes radio telescope between 1998 and 2002, and discovered 11 new sources emitting bright ms-duration bursts. Analysis of the burst arrival times revealed periodicities (with periods in the range 0.4 – 7 s) in the majority of the sources. The periodicities suggested that the new sources, dubbed rotating radio transients (RRATs), were a subset of the radio pulsar population.

Motivated by this discovery, Lorimer et al. (2007) searched archival Parkes radio telescope data taken in 2001 and found a single bright pulse with an initially-estimated peak flux density of more than 30 Jy, in a direction 5° away from the Small Magellanic Cloud. The burst was not re-detected in 90 hours of additional observations of the same sky direction with the Parkes telescope. As can be seen from Figure 1, the radio signal from the burst is "dispersed", that is, the pulse is delayed by the cold ionized plasma along the line of sight, by an amount:

$$\Delta t = \frac{\mathrm{DM}}{k \times f^2},$$

where f is the frequency, $k = 2.41 \times 10^{-4}$ MHz^{-2} pc cm^{-3} s^{-1}, and DM is the dispersion measure, given by:

$$\mathrm{DM} = \int_0^d n_e(l)\ \mathrm{d}l.$$

In the above expression, d is the distance to the source and $n_e(l)$ is the electron number density at the path length l. Lorimer et al. (2007) found that the burst had a DM of 375 pc cm^{-3}, which is several times larger than the expected contribution from free electrons in the Milky Way in this sky direction, thus suggesting an extragalactic origin. This bright burst, known as the "Lorimer burst", is now referred to as FRB 010724.

[1] Laboratoire de Physique et Chimie de l'Environnement et de l'Espace – Université d'Orléans / CNRS, F-45071 Orléans Cedex 02, France
[2] Station de radioastronomie de Nançay, Observatoire de Paris, CNRS/INSU, F-18330 Nançay, France

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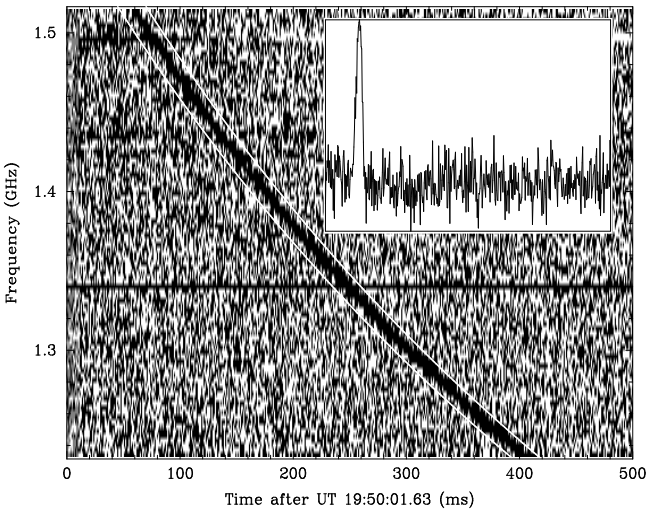

Fig. 1. Signal intensity as a function of radio frequency and time, for the fast radio burst FRB 010724 (the "Lorimer burst") as seen with the Parkes radio telescope. The inset shows the signal integrated in frequency, correcting for the dispersive delay caused by the ionized plasma on the line of sight. Figure taken from Lorimer et al. (2007).

A second FRB candidate was reported by Keane et al. (2011). The burst, known as the "Keane burst" or FRB 010621, was found in a search for pulses in data from the Parkes Multibeam Pulsar Survey. The DM value of this 7-ms burst was again large (about 745 pc cm^{-3}) and in particular larger than the expected DM contribution from the Milky Way (expected to be 533 pc cm^{-3}, according to the NE2001 model of Cordes & Lazio 2002), but because of the small fractional DM excess it was unclear whether the burst had an extragalactic origin. The discovery by Thornton et al. (2013) of a population of four short-duration and high-DM bursts in data from the High Time Resolution Universe survey at the Parkes radio telescope established FRBs as a class of radio transients, likely to be of extragalactic origin. Following these first discoveries, many FRBs were then detected in data from other radio telescopes than Parkes: for instance, FRB 121102 detected with the Arecibo radio telescope (Spitler et al. 2014), or FRB 110523 seen with the Green Bank radio telescope (Masui et al. 2015). Very recently, searches for fast transients with wide field of view instruments such as the Upgraded Molonglo Synthesis Telescope (UTMOST, see e.g. Caleb et al. 2016), the Australian Square Kilometre Array Pathfinder (ASKAP, e.g. Shannon et al. 2018) or the Canadian Hydrogen Intensity Mapping Experiment (CHIME, e.g. CHIME/FRB Collaboration et al. 2019b) have increased the sample of known FRBs dramatically. At the time of writing, the FRB Catalogue* (Petroff et al. 2016) lists the properties of 90 FRBs. Many more will likely be announced and discovered in the coming months and years. Additionally, currently unknown FRBs are likely awaiting discovery in existing radio data from many telescopes.

The vast majority of FRBs detected so far have never been observed to repeat, in spite of deep follow-up observations in some cases, such as those of the Lorimer and Keane bursts mentioned above. Initial follow-up observations of FRB 121102 (Spitler et al. 2014), known as the "Spitler burst", failed to detect additional bursts. However, new observations with Arecibo in May 2015 found ten new bursts, some of which were brighter than the original one (Spitler et al. 2016). Since then, additional bursts from this source have been detected at several radio telescopes around the world (see e.g. Michilli et al. 2018). Periodicity searches have so far failed to find an underlying periodic signal in the burst arrival times. Interestingly, because of its repeating nature, FRB 121102 cannot be caused by a cataclysmic event. In addition, repeating pulses make it possible to study the FRB in much greater details than non-repeating events. So far, no persistent high-energy emission associated with the radio bursts has been detected (see e.g. Scholz et al. 2017). On the other hand, radio interferometric observations of the FRB allowed Chatterjee et al. (2017) to associate it with a low-luminosity galaxy. Optical imaging and spectroscopy by Tendulkar et al. (2017) showed that the host galaxy is a low-metallicity and low-mass dwarf galaxy at a redshift of ~ 0.193. The discovery of a second FRB, FRB 180814.J07422+73, was reported in early

*See `http://frbcat.org/` .

2019 by the CHIME collaboration (CHIME/FRB Collaboration et al. 2019a). Spectra of FRBs 121102 and 180814.J07422+73 are displayed in Figure 2. Complex time and frequency sub-structures are observed in both repeating FRBs, indicating strong similarities between the two sources. Finally, the CHIME collaboration very recently reported the discovery of eight new repeating FRBs, substantially increasing the known population of repeaters (The CHIME/FRB Collaboration et al. 2019). Extensive studies of these new repeating FRBs will enable more detailed comparisons of the properties of repeaters, such as their emission properties or host galaxy properties.

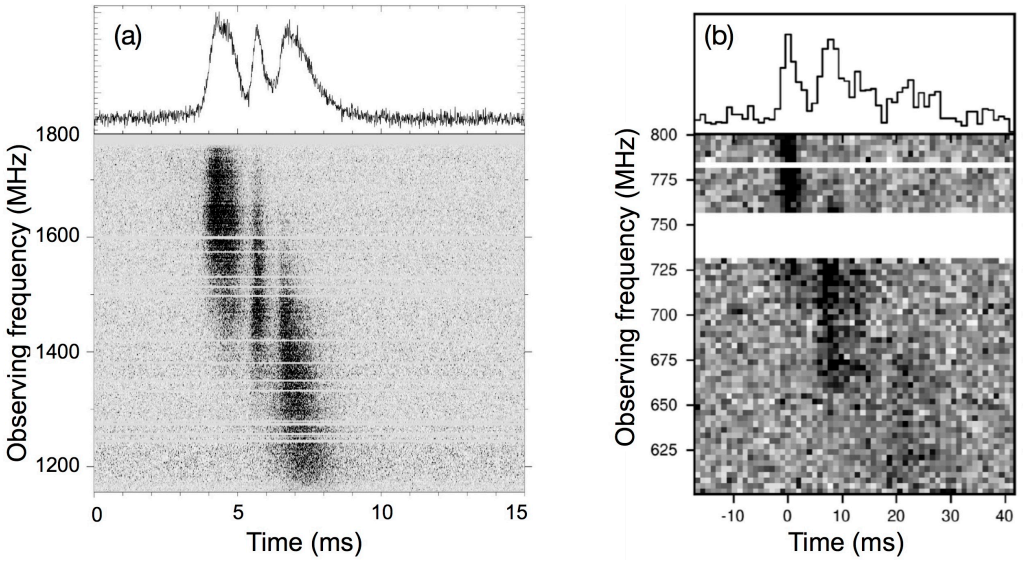

Fig. 2. Intensity as a function of radio frequency and time for the repeating FRB 121102 as seen at 1.4 GHz with Arecibo (left) and for FRB 180814.J07422+73 as seen with CHIME at 0.7 GHz (right). Spectra were corrected for the dispersive delay caused by free electrons on the line of sight of the two FRBs. Figure adapted from Petroff et al. (2019). Both bursts exhibit complex time and frequency structures. See e.g. Hessels et al. (2019) for an analysis of the sub-structures in FRB 121102.

2 FRB properties

In this section, some general properties of the population of FRBs detected so far are briefly presented. We refer the interested reader to the recent comprehensive reviews by e.g. Petroff et al. (2019) or Cordes & Chatterjee (2019) for more exhaustive descriptions of the properties of the FRB population, which are beyond the scope of these proceedings.

Plotted in Figure 3 are the DMs of published FRBs and of known radio pulsars relative to the expected DM contribution from the Milky Way along the line of sight, and as a function of Galactic latitude. A majority of published FRBs have DM values well above the maximum line of sight DM from the Galaxy, indicating extragalactic origins. As is also the case for radio pulsars, DMs can be used to estimate the distances. A DM excess can be defined as follows:

$$\mathrm{DM_E} = \mathrm{DM_{FRB}} - \mathrm{DM_{MW}} = \mathrm{DM_{IGM}} + \left(\frac{\mathrm{DM_{Host}}}{1+z}\right).$$

In the above expression, $\mathrm{DM_{FRB}}$ is the measured DM of the FRB, $\mathrm{DM_{MW}}$ is the DM contribution from the Galaxy over the line of sight, $\mathrm{DM_{IGM}}$ and $\mathrm{DM_{Host}}$ are the DM contributions from the intergalactic medium and the host galaxy, and z is the source's redshift. Although several terms (namely, $\mathrm{DM_{MW}}$, $\mathrm{DM_{IGM}}$, and $\mathrm{DM_{Host}}$) are typically uncertain, the above equation can be used to find a relationship between DMs and redshifts of FRBs. With a much increased sample of FRB DMs and redshifts it may eventually become possible to study

the distribution and density of free electrons in the intergalactic medium (see Keane 2018, for more examples of IGM and cosmological studies using FRB DMs and redshifts).

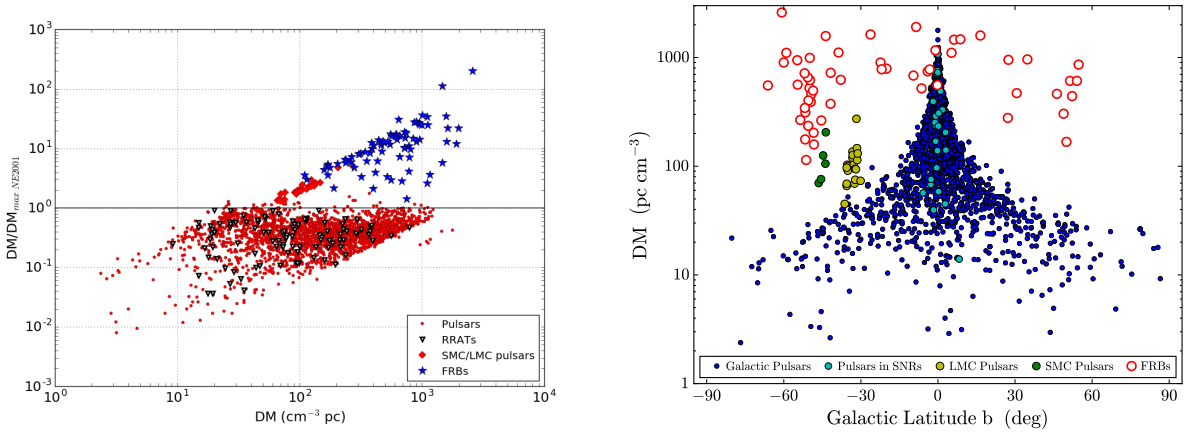

Fig. 3. *Left:* DM value of known Galactic radio pulsars, Galactic RRATs, radio pulsars in the SMC and in the LMC, and of FRBs, relative to the expected DM contribution along the corresponding lines of sight from the Galaxy, according to the NE2001 model. Figure taken from Petroff et al. (2019). *Right:* DM values as a function of Galactic latitude for known pulsars and FRBs. Figure adapted from Cordes & Chatterjee (2019).

With a larger sample of detected FRBs it will also be possible to study their sky distribution, and for instance search FRB directions for clustering (*e.g.*, around galaxy clusters) or anisotropies. Bhandari et al. (2018) analyzed the sky positions of 15 FRBs and found no significant deviation of the positions from an isotropic distribution. Figure 4 shows the distribution of measured fluences and inferred excess dispersion measures for a sample of published FRBs. Significant scatter can be seen in the measured fluences; therefore, it seems unlikely that FRBs could be used as standard candles. For a population of FRBs at different distances (and thus at different excess DMs) one would expect varying fluences; for the currently known sample of FRBs, evidence for such a dependence is seen, as expected. The different selection and observational biases between the various telescopes and surveys that found FRBs appear very clearly in this diagram.

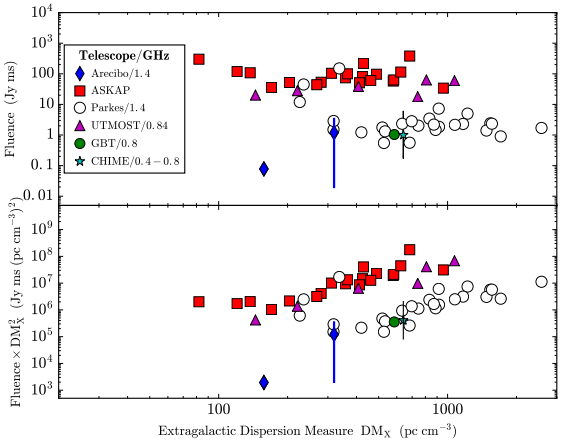

Fig. 4. Fluence – excess DM distribution for known FRBs. The blue line represents the range of fluence values measured for the repeating FRB 121102. Figure from Cordes & Chatterjee (2019).

A number of studies have attempted to estimate the rate of FRBs over the sky. Thornton et al. (2013)

estimated the all-sky rate of FRBs at 1.4 GHz to be of about 10^4 FRBs sky^{-1} day^{-1}. Recent analyses typically converged on rates at 1.4 GHz of a few 10^3 FRBs sky^{-1} day^{-1} with fluences larger than 1 Jy ms (see e.g. Champion et al. 2016; Bhandari et al. 2018). The rates estimated so far correspond to observable FRBs only; indeed, it is not clear at present whether FRB emission is beamed or not. If FRB radio emission is beamed (as in radio pulsars), then the true FRB rate is necessarily larger than estimated from survey detections. In the future, finer estimates of the all sky FRB rate along with a clearer view of the emission (including polarization) properties of FRBs may provide crucial constraints on the progenitor(s) of FRBs.

Among the main unknowns about FRBs are their progenitor(s), and over the past few years a large number of progenitor theories have been proposed. The FRB Theory Wiki[†] (Platts et al. 2018) tabulates proposed FRB theories, and summarizes some of their main features: type of progenitor(s), repeating or non-repeating, emission mechanism, presence of radio, X-ray or gamma-ray counterparts or not, presence of gravitational wave or neutrino counterparts or not, *etc.* In most FRB progenitor theories, FRBs are generated by neutron stars; either isolated neutron stars, neutron stars interacting with their environment or colliding neutron stars. Other theories invoke black hole, white dwarf or more exotic progenitors. As for the other properties of FRBs mentioned above, with a much larger sample of FRBs characterized in detail, more redshift measurements and host galaxy associations, more multi-wavelength and multi-messenger observations (and perhaps, detections), it may eventually become possible to discriminate between FRB progenitor theories. In turn, a better understanding of the origin of FRBs would likely be useful for optimizing FRB search strategies.

3 Prospects

In a little more than a decade, the population of known FRBs has grown from a single event to several tens, including one-off events and repeating FRBs. For some of them, the temporal, frequency, and polarization properties of the burst have been characterized with exquisite details. Yet, as fantastic FRB detectors such as CHIME, ASKAP, FAST, MeerKAT, the Square Kilometre Array (SKA[‡]), *etc.*, are starting to operate or will become available in the future, we could expect that the FRB discovery rate will continue to increase in the coming years, possibly reaching hundreds or thousands of FRB detections every year.

As mentioned in the previous sections, much is still to be learned about FRBs, although enormous progress has been made since the first FRB was found. Examples of open questions for the coming years are: what is the all-sky rate of FRBs? What is their sky distribution? Are there different classes of FRBs? To what extent are repeating FRBs different from non-repeating ones? What are the progenitors of FRBs and what is the emission mechanism? Can we detect them at lower frequencies than 400 MHz, *e.g.* with LOFAR or NenuFAR (see Zarka & Mottez 2016, for simulations of FRB observations with NenuFAR) and at higher frequencies than a few GHz? Could we detect high-energy (X-ray or gamma-ray) emission, neutrinos or gravitational wave emission associated with the radio bursts? What can we learn from FRB radio polarization? Can we obtain better localizations and redshift measurements for more FRB events, including non-repeating ones? Can we identify more host galaxies, and if so, what are their types? Could we clarify the relationship between FRB DMs and redshifts? Can FRBs be used as tools for astrophysics and cosmology? FRB science has so far been extremely exciting, and there is no doubt that even more impressive achievements are yet to come.

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