



Fast Radio Bursts

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Abstract. We summarize our current state of knowledge of fast radio bursts (FRBs) which were first discovered a decade ago. Following an introduction to radio transients in general, including pulsars and rotating radio transients, we discuss the discovery of FRBs. We then discuss FRB follow-up observations in the context of repeat bursts before moving on to review propagation effects on FRB signals, FRB progenitor models and an outlook on FRBs as potential cosmological tools.

Keywords. Radio astronomy—transient astrophysics—fast radio bursts.

1. The transient radio sky

The new class of enigmatic transients known as fast radio bursts (FRBs) are the most recent additions to our state of knowledge of the transient sky. A large number of transient sources are currently known. The known classes of sources emit on timescales ranging from nanoseconds up to as long as years but still short relative to the typical timescales of events in the Universe. Sources from the planetary scale to super-massive black holes can exhibit transient behavior. Astronomers have been observing transient phenomena in the sky for centuries. Some of the early examples include recording of the nearby supernova (SN) that created the Crab Nebula in AD 1054, along with the SNe of AD 1604, 1572, 1181 and 1006. There are some records of possible novae or SNe before AD 1000 as well. All of these historical observations are described in detail in [Stephenson & Green \(2002\)](#). Since then, telescopes probing the entire electromagnetic spectrum have detected many other classes of transient sources. These include the Sun, planets, brown dwarfs, flare stars, X-ray binaries, ultra-high energy particles from cosmic rays, γ -ray bursts, maser flares, active galactic nuclei, radio supernovae and pulsars (e.g. [Cordes et al. 2004](#)). Observations of the radio sky in the last century have resulted in the discovery of several classes of radio transients. These transient sources offer unique opportunities to study

the astrophysics of these objects and the variability timescales could be used as an early diagnostic of source class in future radio transient surveys.

The Sun is the brightest radio source in the sky which varies over an 11-year solar cycle. The solar emission at 10–40 MHz correlating with periods of high sunspot activity was the first radio transient phenomenon observed ([Appleton 1945](#)). The radio bursts from the Sun are labelled as Types I–V and range from a few seconds up to several weeks and are observed at frequencies below 300 MHz ([Dulk 1985](#)). Most of these bursts are caused by variations in the solar plasma. The planets in our solar system which have magnetospheres including Earth, Jupiter, Saturn, Uranus and Neptune show auroral radio emission that lasts a few seconds ([Zarka 1998](#)). Several authors ([Farrell et al. 1999](#); [Zarka et al. 2001](#); [Lazio et al. 2004](#)) have suggested that extrasolar planets would also produce similar bursts and detection of radio emission can lead to direct detection of extrasolar planets.

Beyond the Solar System, the nearby Galactic flare stars (red dwarfs) emit solar-like bursts ranging from milliseconds to days. These flares are broadband emissions. Ultra-cool brown dwarfs and low mass stars have also been seen to emit periodic radio emission ([Hallinan et al. 2007](#)) of the order of 100 μ Jy at frequencies between 5 and 8 GHz. This is the stimulated spectral line emission, typically in the microwave portion of

the electromagnetic spectrum known as the MASER (Microwave Amplification by Stimulated Emission of Radiation) emission and confirm the existence of magnetic fields of the order of a few kG. These bursts are rotationally driven from a star with a dipole field, similar to pulsars. The pulses last for several minutes and repeat on timescales of 2–3 h (Hallinan *et al.* 2008).

The Earth is constantly bombarded with ultra-high energy cosmic rays with energies between 10^{18} – 10^{20} eV. This bombardment results in nano-second duration radio bursts at frequencies of a few Hz to a few hundred MHz that are extremely bright ($\sim 10^6$ Jy; Huege & Falcke 2003). But since the cosmic magnetic fields deflect their paths, their source of origin remains unidentified. Radio emission has also been detected from gamma-ray-bursts (GRBs) and SNe in the form of a radio afterglow. The collision of the supernova shock wave into the ionized circumstellar medium produces incoherent synchrotron radiation which is visible across a range of radio frequencies (Weiler 1983).

2. Pulsars and RRATs

Over thirty years after Chadwick's discovery of the neutron, and the prescient remarks of Baade and Zwicky that neutron stars might be formed in supernova explosions, Jocelyn Bell and Anthony Hewish at Cambridge found sources which emitted individual pulses with durations of 10s of milliseconds (Hewish *et al.* 1968). Since then the field of pulsar astronomy has evolved by carrying out numerous surveys with large radio telescopes. At the time of writing, the ATNF (Australia Telescope National Facility) data network has recorded about 2613 pulsars, including sources in nearby satellite galaxies (Manchester *et al.* 2005), and their connection with rapidly rotating highly magnetized neutron stars has been firmly established. Pulsars are excellent tools to study a wide variety of astrophysical phenomena, including neutron star physics, the interstellar medium, general relativity and gravitational waves.

Although the precise periodicity is the main characteristic of a pulsar signal, another class of transients, known as Rotating Radio Transients, or RRATs, are a group of Galactic pulsars that emit sporadic single pulses. These were first detected by McLaughlin *et al.* (2006) while processing the data from the Parkes Multi-beam Pulsar Survey (PM survey; Manchester *et al.* 2001). There are 112 RRATs discovered so far¹. The pulses from RRATs sometimes repeat but not regularly,

like those of pulsars and some have been observed at only one epoch. Hence RRATs are easily detectable as single isolated pulses, rather than as a repeating signal.

The lack of detection in a periodicity search suggests that RRATs are either much more weakly emitting, or in fact 'off', during times when we do not detect pulses. Despite this, by examining time differences between the arrival times of pulses, underlying periods have been estimated for almost 88 RRATs, for which enough pulses are seen together. Period derivatives have been estimated for 29 RRATs. The inferred source sizes, the underlying rotation periods, as well as the expected time-scales for transient behaviour all point towards RRATs being Galactic neutron stars.

In addition to RRATs, some pulsars are seen to emit giant single pulses occasionally. Their flux densities can exceed hundreds and thousands of times the mean flux density of regular pulses from the pulsar. For example, the giant pulses (GPs) from the Crab pulsar which led to its discovery show pulses with an intensity up to 1000 times that of an average pulse. The GPs are also very short in duration. Hankins *et al.* (2003) found pulses as short as 2 ns from the Crab pulsar. GPs from B1937+21 were observed for the first time by Wolszczan *et al.* (1984) but were recognized later by Cognard *et al.* (1996). The duration of these GPs is short compared to the period of the pulsar, lasting on the order of 10 ns (Soglasnov *et al.* 1984). The amplitude distribution of GPs is a power-law (Popov & Stappers 2007), whereas the amplitude distribution of pulses from many pulsars is log-normal (Rickett 1976).

3. Fast radio bursts

A renewed interest in finding other radio transients along with the discovery of RRATs led a number of groups to more routinely perform single-pulse searches in addition to periodicity searches on pulsar survey data. While re-processing data from a pulsar survey of large and small Magellanic clouds (LMC, SMC) using the multibeam receiver from the 64-m Parkes radio telescope, Lorimer *et al.* (2007) found an exceptionally bright burst that lasted about 12 milliseconds. The DM was found out to be anomalously high, compared to maximum DM due to the electrons in the Milky Way in that direction. This event, known as the 'Lorimer burst', had a peak flux density of ~ 33 Jy and a DM of 375 pc cm^{-3} . The Galactic DM contribution along the line of sight of this burst predicted by the NE2001 model is 45 pc cm^{-3} , i.e. only 12% of the total measured DM value. Therefore, the excess DM indicated that the

¹For an up-to-date list, see <http://astro.phys.wvu.edu/rratalog>.

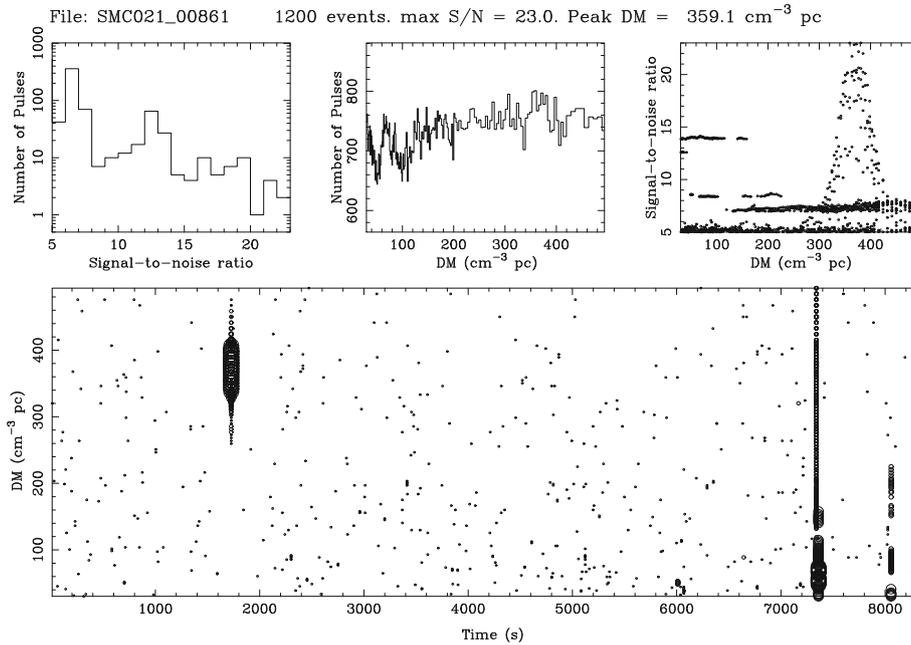


Figure 1. The output of a single-pulse search analysis done by showing the detection of the Lorimer burst.

source is located outside our Galaxy. Figure 1 shows an output of a single-pulse search analysis done by Lorimer *et al.* (2007) and their detection of the Lorimer burst. It is seen in the DM versus time plot as a strong pulse and with $S/N > 20$ as seen in the S/N versus DM plot at the top right corner.

This burst was debated for quite some time. In particular, Burke-Spolaor *et al.* (2011a) found bursts at high DMs. The Parkes multibeam receiver consists of 13 beams each with a beamwidth of $\sim 14'$ and the Lorimer burst was seen in three beams of the Parkes multibeam but these new bursts, known as ‘peryttons’ were seen in all 13 beams. The peryttons were seen to mimic the dispersive signal coming from an astrophysical pulse that has propagated through cold plasma. More such bursts were found in the reprocessing of the Parkes Multibeam (PM) pulsar survey data (see, e.g., Bagchi *et al.* 2011) which were all very hard to reconcile with an astrophysical origin. The general consensus in the community at that time was leaning towards a similar conclusion for the Lorimer burst.

The story took a more positive twist when Keane *et al.* (2012) found another similar burst at 1.4 GHz very close to the Galactic plane which was seen in only one beam and at a higher DM (746 pc cm^{-3}). Further evidence that these bursts are astrophysical came only after the discovery of four bursts in the High Time Resolution Universe (HTRU) survey at 1.4 GHz (Thornton *et al.* 2013). These highly dispersed pulses are now known as ‘Fast Radio Bursts’ (FRBs) and are labelled

in YY/MM/DD format. A single dispersed burst would be classified as an FRB if it is bright, has a pulse width of a few ms and a DM greater than the expected Galactic DM contribution along that line-of-sight. It should be noted that the NE2001 model has uncertainties up to 40% in certain directions. For example, in the case of FRB 010621, $H\alpha$ observations of the diffuse ionized gas along the line of sight showed that the pulse most likely resides in the Galaxy and the excess DM is caused by localized density enhancements along the line of sight (Bannister & Madsen 2014).

After the discovery of four bursts (FRBs 110220, 110626, 110703, 120127) by Thornton *et al.* (2013), a number of pulsar archival surveys were searched for FRBs using the single-pulse search method up to a much higher DM. The typical values of DM for Galactic pulsars range from 2 pc cm^{-3} to 1800 pc cm^{-3} , where high DM pulsars are near the center of our Galaxy (see Fig. 2). Usually high latitude pulsar surveys are processed for DMs up to 300 pc cm^{-3} while searching for Galactic pulsars and RRATs. This is reasonable because there are about 600 pulsars that have DM values greater than 300 pc cm^{-3} and most of these pulsars are very close to the Galactic Centre with longitudes within $\pm 50^\circ$ and latitudes within $\pm 5^\circ$.

Soon after this, FRB 011025 was discovered in the processing of HTRU intermediate latitude survey. The fact that all FRBs were detected only in the data from the Parkes telescope raised some concern at that time. In 2014, FRB 121102 was discovered with the

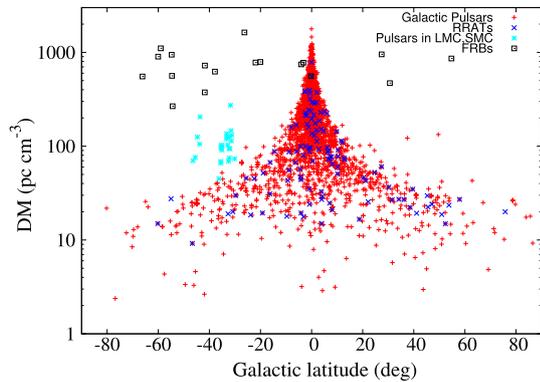


Figure 2. The DM latitude dependence (b) for pulsars, RRATs and FRBs. The Galactic pulsars and RRATs fall under the envelope proportional to $\text{cosec}(b)$ which is expected for the dispersion caused by electrons of a finite scale height.

305-m Arecibo telescope in the processing of the Pulsar Arecibo L-band Feed Array (PALFA) survey (Cordes *et al.* 2006) at 1.4 GHz. This burst was detected towards the Galactic anti-center at a DM of 557 pc cm^{-3} and this discovery cleared doubts about FRBs being some phenomena related to the Parkes telescope only.

The development of a real-time transient pipeline at the Parkes telescope using the multi-beam receiver led to the discovery of FRB 140514 at 1.4 GHz (Petroff *et al.* 2015a, b, c). The authors were aiming to search the fields of previous FRBs to look for repeat events and FRB 140514 was detected in the same field as FRB 110220 but at a much lower DM. They argued that their proximity is due to sampling bias in their choice of observing location. After the real-time detection, follow-up observations were carried out with 12 telescopes observing from X-ray to radio wavelengths but they were unable to identify any afterglow-like variable multi-wavelength counterpart. When a SN or a long duration gamma-ray burst (GRB) goes off, a counterpart is detectable as an object of varying brightness. This type of afterglow is observable on time-scales ranging from hours (for a long GRB) to days (for typical SNe) and therefore this lack of detection suggested that FRBs are unlikely to be associated with long duration GRBs or SNe.

Another real-time discovery (FRB 131104) followed with the same pipeline in a targeted observation of the Carina dwarf spheroidal galaxy at 1.4 GHz (Ravi *et al.* 2014). The dispersion measure of this FRB exceeded the maximum predicted line-of-sight Galactic contribution by a factor of 11. Follow-up observations of 100 h with the Parkes telescope did not detect any repeat events from this location. A γ -ray transient has recently been proposed to be associated with this FRB at the 3.2σ to 3.4σ confidence level

with *Swift*. This transient, J0644.5–5111, was seen for ~ 380 s. This is somewhat longer than most long-duration GRBs detected by *Swift*. They suggested that the γ -ray emission was generated by shocked relativistic plasma in a cosmological explosion, or in an accretion episode associated with a supermassive black hole. However, in a follow-up study, carried out observations of the field of FRB 131104 with the Australia Telescope Compact Array (ATCA) for 2.5 years beginning 3 days after the event and found no radio afterglow coincident with the γ -ray event. They argued that a true association is not significantly more likely than the probability of an unassociated occurrence.

Although FRBs were detected with two telescopes, all of the above mentioned FRBs were discovered between 1–2 GHz. This frequency coverage was broadened by Masui *et al.* (2015) with their discovery of FRB 110523 with the Green Bank Telescope (GBT) in archival hydrogen intensity mapping survey carried out in the frequency range 700–900 MHz. This discovery, which showed convincing evidence for multiple scattering screens along the line-of-sight, strengthened the argument that FRBs are astrophysical phenomena.

Five additional FRBs were discovered in the processing of HTRU high latitude survey by Champion *et al.* (2016) with FRB 121002 detected at a DM of 1629 pc cm^{-3} , the highest DM found so far. Efforts of searching for multi-wavelength counterparts and finding associations with host galaxy continued. In mid-2016, the discovery of FRB 150418 was reported with the identification of a fading radio transient that lasted over the course of six days after the FRB event (Keane *et al.* 2016). The authors used it to identify a host galaxy at a redshift of 0.492. Further observations by Williams & Berger (2016) and Vedantham *et al.* (2016) suggested that the observed variable radio emission is instead due to an active galactic nuclei (AGN) activity and are unrelated to FRB 150418.

In 2015, FRB 150807 was detected with the Parkes telescope while timing observations of a millisecond pulsar were being carried out. This FRB has a DM of 266.5 pc cm^{-3} , which is the lowest DM for an FRB found so far. This FRB is very bright (~ 12 Jy) and is also linearly polarized.

Very recently, Caleb *et al.* (2017) discovered three FRBs at 843 MHz in real-time with the UTMOST array at the Molonglo Observatory Synthesis Telescope in Australia. These are the first FRBs discovered with an interferometer (160317, 160410, 160608). UTMOST array consists of an east–west cylindrical paraboloid divided into two ‘arms’, each 11.6-m wide and 778-m

long. They performed a 180-day survey of the Southern sky and followed up at these locations for 100 h which resulted in no repeat events. The discovery of FRB 150215 was recently published by [Petroff et al. \(2017\)](#) in real time with a DM of $1105.6 \text{ pc cm}^{-3}$ and was found to be $\simeq 43\%$ linearly polarized with very low RM. This burst was followed-up with 11 telescopes to search for radio, optical, X-ray, gamma-ray and neutrino emission; however, no transient or variable emission was found to be associated with the burst. Also, no repeat pulses were observed in 17.25 h of observing. Finally, the most recently discovered FRB at the time of writing is 170107 found during early observations with the Australian SKA Pathfinder, ASKAP ([Bannister et al. 2017](#)). Like the FRBs 010724 and 150807, this is a bright source. Its discovery with ASKAP, another interferometric instrument, shows great promise of this and other wide-field instruments deploying phased-array feeds in the coming years.

4. Perytons revealed

By 2015, the development of realtime burst detection schemes allowed the source of the perytons to be identified. Around 25 perytons were recorded since 2011 ([Burke-Spolaor et al. 2011a](#); [Kocz et al. 2012](#); [Baggchi et al. 2012](#); [Saint-Hilaire et al. 2014](#)) and were observed only during office hours and on weekdays. This suggested that they might be a form of human-generated interference. [Petroff et al. \(2015a, b, c\)](#) demonstrated that a peryton can be generated at 1.4 GHz when a microwave oven door is opened prematurely and the telescope is at an appropriate relative angle.

Inside a microwave, the magnetron pulls electrons from the power source and then uses magnets to rotate them around inside a vacuum. This generates microwaves and the magnetron power cycle can be set to a duration depending on the manufacturer. If the microwave door is opened before this cycle is complete then the radio emission escaping from microwave oven during this phase can generate a peryton signal. They performed specific tests to verify this and detected three perytons on three separate days. By comparing properties of perytons and FRBs, [Petroff et al. \(2015a, b, c\)](#) demonstrated that perytons are strongly clustered in DM and time of the day unlike FRBs which are uniformly distributed. Most notably, the Lorimer burst (FRB 010724) was detected at 4 a.m. From these observational differences, they concluded that FRBs and perytons arise from different origins and that FRBs are indeed astrophysical in origin.

Table 1. List of FRB follow-up observations.

FRB	Duration (h)
010724	>200
090625	~34
110220	~2
110626	~11
110703	~10
120127	~6
131104	~100
150807	~215
121002	~10
140514	~19
130626	~10
130628	~9

5. Repeating FRBs

All of the FRBs have been searched for repeat bursts but in all but one case so far were unsuccessful. A list showing the known radio follow-up observations is provided in Table 1. Initial follow-up observations of FRB 121102 were carried out for a few hours with no detection ([Spitler et al. 2014](#)). In 2015, this FRB was extensively observed with the Arecibo telescope around the best known sky position. This effort resulted in ten additional bursts ([Spitler et al. 2016](#)) in three hours of observations, confirming it as the only repeating FRB source observed so far.

These detections motivated further follow-up multi-wavelength campaigns and [Scholz et al. \(2016\)](#) found five bursts with the GBT at 2-GHz, and one at 1.4 GHz with Arecibo. All of these 17 repeat bursts have the same DM as that of FRB 121102. This provided strong evidence that the bursts were originating from the same source.

The bursts appear to cluster in time but no underlying periodicity has been detected yet. The peak flux densities were in the range of 0.02–0.3 Jy at 1.4 GHz, suggesting that weaker bursts are also produced, preferably at a higher rate. No evidence for scatter broadening or polarization is seen in any of these bursts, however, after fitting a power-law model ($S_\nu \propto \nu^{-\alpha}$) to burst spectra, the spectral index was found to range from -10 to $+14$. This varying spectral index could be intrinsic to the source or due to propagation effects as suggested by [Scholz et al. \(2016\)](#).

The repeating bursts from FRB 121102 led to targeted interferometric localization efforts. In 2016, 83

hours of simultaneous observations with the Karl Jansky Very Large Array (VLA) and the Arecibo telescope, spanned over six months, detected nine bursts in the 2.5–3.5 GHz band and reported the first sub-arcsecond localization (Chatterjee *et al.* 2017). The beam formed single-pulse search and millisecond imaging resulted in detection of a persistent variable radio counterpart with a flux density of 180 μJy (Marcote *et al.* 2017) and a star-forming host galaxy at a redshift of 0.19 (Tendulkar *et al.* 2017). The host galaxy is very small with a stellar mass of $(4\text{--}7) \times 10^7 M_{\odot}$. The European very-long-baseline interferometric (VLBI) network at 5 GHz detected 4 bursts and showed that the projected separation between the persistent radio source and FRB is less than 40 pc, suggesting a strong physical link.

All of the 23 FRBs mentioned above have DMs exceeding the Galactic DM contribution by a factor between 1.5 to 11. Although the NE2001 model could be uncertain up to 40% along certain lines-of-sight, these events can still be distinguished from the other radio transients. Figure 2 shows the DM distribution as a function of latitude for all radio pulsars and FRBs. The pulsars in the LMC and SMC can be clearly seen above the Galactic pulsar population with additional DM coming from the electrons between LMC, SMC and the Earth and from the LMC, SMC itself.

However, FRBs have no correlation between DM and latitude dependence indicating that the total DM includes a large extragalactic component. Ionized gas in galaxies and in the IGM are therefore plausible sources for this extragalactic part of the DM. The measured DM follows as ν^{-2} which shows that the electromagnetic signal passes through the cold plasma. Some authors (e.g. Loeb *et al.* 2014) have suggested that the excess DM might arise from flaring stars. But the plasma near the surface is not cold and the resulting signal would not follow the ν^{-2} behavior which is seen for all FRBs. If the free electron distribution in the host galaxy is similar to that in our Galaxy, then a host DM can be estimated. For $z \geq 0.2$, the DM contribution from the IGM is expected to dominate for FRBs at higher latitudes (Ioka 2003; Inoue *et al.* 2004). Then the IGM contribution can be computed by subtracting the host DM and DM due to the Milky Way from the total measured DM. Since the DM due to the IGM depends on the redshift, this can be used to estimate a redshift of an FRB. The inferred redshifts for the known FRBs range from 0.19–2.2. Only one independent measurement has been carried to date for FRB 121102 at $z = 0.193$ (Tendulkar *et al.* 2016). Cordes & Wasserman (2016) argued that the redshifts can be significantly overestimated if they are based on the assumption that the extragalactic portion of DM is

dominated by the IGM as it is also possible that the host galaxy dominates the extragalactic DM contribution.

6. Propagation effects on FRB signals

In the case of FRBs, the Galactic ISM, IGM, host ISM, and intervening galaxy or galaxy clusters all cause turbulence-induced scatter broadening. The scattering in FRBs can be used to study turbulence in the IGM and in other galaxies. FRB scattering timescales are within the range spanned by pulsars but are many orders of magnitude larger than pulsars at similar Galactic latitudes.

Nine out of currently known FRB sources show asymmetric pulse broadening caused by scattering from small-scale electron-density variations. The left panel of Fig. 3 shows FRB profiles with no scattering and the FRBs with scattering are shown in the right panel. The horizontal time scale is 60 ms for each profile.

The measured pulse broadening for FRBs is much larger than expected from the Milky Way for the directions of FRBs but the broadening is smaller than would be expected from the τ –DM relation for Galactic pulsars having the same DM. Milky Way can only account for scattering timescales less than a microsecond. Observations of scattering along extragalactic lines of sight by Lazio *et al.* (2008) and theoretical calculations by Macquart & Koay (2013) suggested that scattering in the IGM is several orders of magnitude lower than in the ISM. If the IGM contributed enough to the scattering then that would require a level of turbulence an order of magnitude higher than encountered at the Galactic center. The low density diffuse IGM cannot support such density fluctuations and therefore cannot reproduce the measured scattering for FRBs. The scattering contribution from intervening galaxies and galaxy clusters near the line-of-sight is not an important effect because the probability of this alignment is very low. Note the probability of an intervening source within $z < 1$ is less than 0.05 (Roeder & Verreault 1969). This makes the contribution from the host galaxy the most prominent source of scattering in FRBs. This assumes that the ISM in the host galaxy has the same properties as in the Milky Way at all redshifts. But at higher redshifts, observations suggest that the ISM in those galaxies was more turbulent and dense ($z \sim 2$; Xu & Zhang 2016). Overall, the scattering timescale provides valuable insights into the IGM turbulence concerning the detailed structure of density and magnetic field of the IGM.

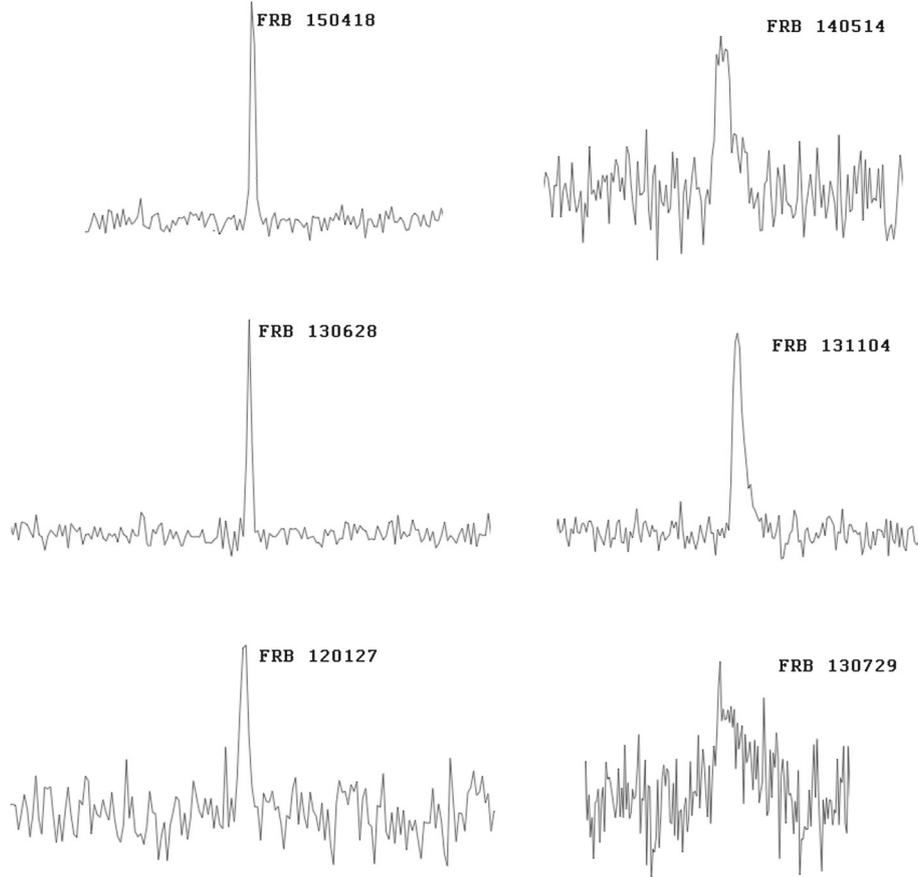


Figure 3. FRBs with no scattering are shown in the *left panel* and FRBs with scattering are shown in the *right panel*. The horizontal time scale is 60 ms for each profile.

For astrophysical sources, the electric field vectors are plane waves. The rotation of the angle of linear polarization is called rotation measure (RM) and it is proportional to the line of sight component of magnetic field ($B_{||}$) weighted by electron density n_e . RM is measured in units of rad m^{-2} . The measurement of RM and DM provide the average magnetic field strength along the line-of-sight:

$$\langle B_{||} \rangle = \frac{\int_0^d n_e B_{||} dl}{K \int_0^d n_e dl}. \quad (1)$$

Here the magnetic field strength is in μG . This relation works very well for Galactic pulsars. However, in the case of FRBs, it cannot be used directly to estimate the intergalactic magnetic field as FRBs are cosmological sources. The RM and DM have different redshift dependencies. As noted in [Akahori et al. \(2016\)](#), the DM at cosmological scale is dominated by contributions from the warm-hot intergalactic medium (WHIM) in filaments and from the gas in voids. The RM is induced mostly by the hot medium in galaxy clusters, with only

a fraction of it produced in the WHIM. They modify equation (1) as

$$\langle B_{||} \rangle = \frac{\langle 1+z \rangle_{\text{WHIM}} \int_0^d n_e B_{||} dl}{f_{\text{DM,WHIM}} K \int_0^d n_e dl}. \quad (2)$$

Here $f_{\text{DM,WHIM}}$ is the fraction of the total DM due to the WHIM and can be evaluated for a given cosmology model using the DM of an FRB. With this simple modification, the density-weighted line-of-sight magnetic field strength of the intergalactic medium in filaments of the large-scale structure can be reconstructed.

To constrain the emission mechanism, we need polarization information of FRBs. As of now, only a few FRBs have shown polarization. FRBs 140514 is found to be 20% circularly polarized but no linear polarization was detected and hence the RM could not be determined ([Petroff et al. 2015a, b, c](#)). The authors concluded that this polarization is intrinsic to the FRB and suggested that if FRBs emit coherently then there would have been intrinsic linear polarization but it may have

been depolarized by Faraday rotation caused by passing through strong magnetic fields and/or high-density environments. Faraday rotation was measured for FRB 110523 which was detected by Masui *et al.* (2015). This FRB is 44% linearly polarized with a best-fitting RM of $-186.1 \text{ rad m}^{-2}$. The average line-of-sight component of the magnetic field is $0.38 \mu\text{G}$. The authors claimed that this magnetization is local to the FRB source as the contributions to the RM along this line-of-sight within the Milky Way and from the IGM are small. FRB 150418 was found to be only 8.5% linearly polarized with no circular polarization (Keane *et al.* 2016). The authors determined RM of 36.0 rad m^{-2} but mentioned that this measurement is not very precise since the linear polarization is very low. They placed an upper limit on the electron weighted IGM magnetic field strength of $\sim 0.4 \mu\text{G}$. Ravi *et al.* (2016) found FRB 150807 to be 80% linearly polarized giving a RM of 12.0 rad m^{-2} . They constrained the average line-of-sight magnetic field to be $\langle 21(1 + z_{\text{mean}}) \rangle \text{ nG}$, where z_{mean} is the mean redshift of the intervening electron density distribution.

Although currently we have only a few Faraday rotation measurements, the development of polarization triggering modes along with the real-time detection system at Parkes and at other telescopes will enable us to get polarization information for all detections. The measurement of RM can give useful insights into the local environment around the FRB sources.

7. FRB progenitor models

The physical nature and the progenitors of FRBs still remain a mystery. Although a large number of theories exist to explain their origin, none of them have been conclusively proven correct from the observations. The proposed model should be consistent with the very high event rate of FRBs and should explain the large DMs, timescales, and brightness as well. The best estimate for FRB all-sky event rate is $3.3_{-2.2}^{+3.7} \times 10^3$ events per day per sky (Rane *et al.* 2016). The currently proposed models involve sources which are either cataclysmic in nature (i.e. producing only one burst), or capable of producing multiple bursts.

The cataclysmic models include merging or collapsing of compact objects. Falcke & Rezzolla (2014) proposed that a neutron star created above the theoretical mass limit would be supported by centrifugal force for an extended period of time, until the star is spun down enough due to various torques, the most dominant of which may be the magnetic dipole spin down

so that centrifugal force can no longer support the star. At this point, the neutron star would collapse into a black hole. The magnetosphere is the only part of the neutron star which will not disappear in the collapse as it is well outside the neutron star. The entire magnetic field should in principle detach and reconnect outside the event horizon. This results in large currents producing strong shock and intense electromagnetic emission as an ordinary pulsar turns into a blitzar, which is bright enough to explain the observed fast radio bursts. The characteristic timescale for such an event is less than a millisecond. Falcke & Rezzolla (2014) also argued that only a few per cent of the neutron stars are needed to be supramassive in order to explain the observed FRB rate.

Some authors have discussed the binary neutron star mergers as a possible origin of FRBs (Piro 2012; Totani 2013; Wang *et al.* 2016) as both rates are consistent. At the time of coalescence, the magnetic fields of neutron stars are synchronized to binary rotation and the radiation mechanism due to magnetic braking seems favorable to explain the millisecond duration of FRBs before merging into a black hole (Totani 2013). In a NS binary in which one NS is highly magnetized compared to the other one, the magnetic torques spin up the magnetized NS draining the angular momentum from the binary and accelerating the inspiral. An electromotive force induced on one NS accelerates electrons to an ultra-relativistic speed and the resultant coherent curvature radiation from these electrons moving along magnetic field lines in the magnetosphere of the other NS is responsible for the observed FRB signal. The coalescence would leave behind a rapidly rotating black hole which could be a possible source of gravitational wave event (Piro 2012; Wang *et al.* 2016).

FRBs could be produced in another scenario such as merging of white dwarfs (Kashiyama *et al.* 2013) in which the coherent emission is produced from the polar region of a massive rapidly rotating and magnetized white dwarf formed after the merger. A SN Ia is one possible counterpart in this model but the lack of any such associations from current observations question this model for FRBs. Other interesting models could also explain a sub-class of FRBs. These include NS-BH mergers (Mingarelli *et al.* 2015), BH-BH mergers (Zhang 2016; Liebling & Palenzuela 2016) the discharging of charged black holes (Liu *et al.* 2016), and evaporating BHs (Keane *et al.* 2012).

The discovery of a repeating FRB, however, rules out the cataclysmic models at least for this FRB or for a subset of FRBs. In this scenario, if FRBs are observed for long enough time with more sensitivity, either all or

some of them might be seen to repeat. However, this is still under debate and there is no robust evidence yet for one or multiple FRB progenitors, if there are any, from observations. We cannot rule out the cataclysmic models completely as of now, but we can place strong constraints on what type of progenitors could be producing this type of emission. Most of the known FRBs have been followed up in radio or at other wavelengths as of now. However, not all non-detections have been reported and hence it is difficult to conclude if any other FRB should have been seen to repeat. It could be possible that the repeater belongs to a population of sources at a different evolution phase from other FRBs. But we see no distinction in the observed properties of repeater and other bursts. We still need more FRBs to support or refute this kind of hypothesis. It should also be noted that as mentioned earlier, the sensitivity of Parkes is less than that of Arecibo so there is a possibility that they all repeat but might be below our detection threshold. In fact, the faintest Arecibo detections have flux densities an order of magnitude smaller than those of the faintest Parkes FRBs. In this case we are only detecting the brightest pulse from the source and other pulses remain undetected.

The narrowest pulses from FRBs constrain the emission region size based on the light travel time. FRB 150807 has the narrowest pulse of 0.35 ms. This gives us an emission region size of ~ 105 km which is comparable to sizes of compact objects. Neutron stars also generate coherent emission from a small emission region and produce large amount of energy similar to those observed from FRBs. Based on these current observations, we only discuss a handful of the most promising models that could explain the repeatable origin of FRBs. Most of these models include some relation with neutron star emission.

Cordes & Wasserman (2016) proposed that FRBs are associated with bright pulses from extragalactic pulsars. Some pulsars (for example, the Crab pulsar) are known to emit giant pulses and the NS formation rate in a Hubble volume is comparable to the FRB rate. In this case, the emission will be rotationally driven. If pulsars at distances within 100 Mpc emit such bright pulses then this population of pulsars within this distance may be the source of FRBs. However, the giant pulses emitted from the Crab are not typical of the pulsar population as a whole. Taking this into account, the authors argued that the giant pulses from extragalactic pulsars might be magnified through gravitational lensing of individual stars. Although the energetics and rate arguments are consistent with the properties of FRBs, it should be noted that the probability of seeing a repeat

pulse from such an object is extremely low on human timescales.

Pen & Connor (2015) suggested that FRBs are bursts from extragalactic but non-cosmological young pulsars and magnetars. Young neutron stars are energetic and are embedded in a supernova remnant (SNR). If the number of young pulsars is proportional to the core-collapse supernova rate and each pulsar emits a giant pulse every 100 days or so, then the FRB rate is consistent within a local volume of about 200 Mpc (Connor *et al.* 2016). Within a few hundred years of a core-collapse SN, the ejecta is confined within one parsec. This region could contribute to the excess DM. The magnetar model is based on the observed properties (polarization, DM, scattering) of the radio loud magnetar in our Galactic center. Pen & Connor (2015) suggested that such galactic center magnetars within a few hundred megaparsecs could be the source of FRBs in which the emission will be magnetically powered and the excess DM could come from the overdense region near the galactic center of the host galaxy. However, it should be noted that the population of such magnetars is smaller than that of young pulsars (Kaspi & Beloborodov 2017).

The soft gamma repeaters (SGRs) are a type of magnetars which exhibit giant flares due to relativistic explosions in the magnetospheres (Lyutikov & Lorimer 2016). In addition, they also produce non-thermal radio emission or hyperflares as suggested by Lyutikov (2002). Popov & Postnov (2013) showed that the energetics of such hyperflares are consistent with that of FRBs. However, no radio emission was detected at Parkes during SGR 1806–20 giant flare (Tendulkar *et al.* 2016) which provides arguments against the magnetar association. If indeed FRBs are related to magnetar giant flares, then we should expect to detect prompt high-energy afterglow and a very bright optical flash (Lyutikov & Lorimer 2016).

The supergiant pulse models mentioned above invoke nearby galaxies that are not at cosmological distances and therefore are challenged by the fact that the repeater is located in a host galaxy at redshift $z = 0.193$. Initial observations of the repeater did not show extended emission in radio, IR or in H_α which suggested that this FRB is not associated with an HII region or a pulsar wind nebula as the luminosity is very high and that the radio persistent source is unlikely to be an AGN since no optical or X-ray signatures are seen.

After the localization of FRB 121102 and based on the observed properties of this FRB, some of the above models can be tested. Murase *et al.* (2016) suggested that if FRBs are indeed powered by a young

NS then the counterparts of FRB can be observed as quasi-radio nebular sources. The quasi-steady counterpart of FRB 121102 is broadly consistent with theoretical predictions. The authors considered young NSs including magnetars as the source of FRBs and calculated associated nebula emission of magnetar and pulsar-driven supernovae including super-luminous supernovae (SLSNe). Metzger *et al.* (2017) proposed that the repeated bursts from FRB 121102 originate from a young magnetar remnant embedded within a young hydrogen-poor SNR since the properties of the host galaxy of FRB 121102 are consistent with those of long-duration GRBs and hydrogen poor SLSNe. The host galaxy of FRB 121102 is a dwarf galaxy in which SLSNe and long-duration GRBs are common. Further studies of this FRB will tell us more about the neighbourhood of this galaxy and if it has any companions.

The energetics and rates timescales of NS binary merger are comparable to FRBs. Also, the timescales of these merger events are consistent with FRB widths suggesting this model could well explain the origin of FRBs. However, if this is true, the existence of repeating FRB 121102 requires two distinct classes of FRBs to exist. If, on the other hand, all FRBs are indeed repeating sources but are not detectable due to low sensitivity, then the young magnetars could well explain the origin of repeated bursts.

8. FRBs as cosmological tools

The standard cosmological model or the Λ -Cold Dark Matter (Λ -CDM) model attempts to explain the existence and structure of the cosmic microwave background, the large-scale structure in the distribution of galaxies, abundances of hydrogen, helium, and also the accelerating expansion of the universe. The letter Λ represents the cosmological constant associated with the dark energy which is used to explain the accelerating expansion of the Universe. The measurement from the Planck Collaboration (2016) estimates the fraction of the total energy density of our Universe, that is dark energy to be $\sim 69\%$. In addition, the dark matter component, supposed to be consisting of the hypothetical particles called as weakly interacting massive particles (WIMPs) accounts for the gravitational effects observed in large-scale structures and is currently estimated to constitute about $\sim 26\%$ of the total energy density of the Universe. The remaining $\sim 5\%$ comprises all ordinary matter that is made of protons and neutrons that make up atoms and we refer to it as the baryonic matter (detectable matter). Observations

tell us that all the matter in stars, gas, and dust between galaxies is not enough to account for all the baryon content. In the low-redshift IGM, approximately 30% of the baryons reside in the warm intergalactic phase observed in photoionized diffuse Ly α absorption and $\sim 15\%$ in the hot gas traced by OVI absorbers. An additional 5% may reside in circumgalactic gas (material in galaxy halos), 7% in galaxies, and 4% in clusters (Nicastro *et al.* 2008; Shull *et al.* 2012). This leaves a large fraction ($\sim 29\%$) that is still not accounted for and is referred to as ‘missing baryons’. Finding these missing baryons is crucial to validate our standard cosmological model.

Most of the missing baryons are believed to be residing in the warm-hot IGM (WHIM) where the temperatures are high (10^5 – 10^7 K) and density is low. Therefore no significant absorption or emission is seen posing difficulties in detecting baryons using the conventional spectral line diagnostics. If we could measure the redshifts of FRBs independently then FRBs would be capable of detecting every single ionized baryon along the line of sight and thus could be direct detection of the missing baryons. In the low-redshift universe ($z < 3$) where the helium is fully ionized (McQuinn *et al.* 2009) and homogeneously distributed such that $n_e \propto \Omega_b(1+z)^3$ (Ioka 2003), where Ω_b is the baryon density. And $DM_{IGM} \propto n_e$, hence the DM- z relation can be used to estimate the baryon density along the lines of sight of FRBs.

Also, most of the dark matter is believed to reside in galactic halos, however, much less than half of the baryons are observed to lie within these halos (McQuinn 2014). Using the DM- z relation for FRBs as a cosmic ruler is not quite straightforward as the DM of an FRB varies as it travels through the IGM. McQuinn (2014) calculated the probability distribution functions (PDFs) of DMs for FRBs with $z \sim 1$ and showed that the dispersion in DM depends strongly on the strength of the feedback. The feedback is provided through stellar winds, supernovae, or AGN activity. A strong feedback scenario refers to baryons extending out to a larger radius beyond the dark matter halo radius and the PDF of DMs is more concentrated giving a Gaussian distribution in DMs, whereas, in the case of weak feedback scenario, the DM distribution is much broader. Therefore, we would get different DM distributions for FRBs at the same z depending on how far the baryons are stretching the halos of the galaxies along the line of sight and location of baryons within the halo. We would also need to find redshift measurements for many FRBs to account for the effects of variance in the sightlines.

Nonetheless, extragalactic DM measurements of FRBs do provide means of directly measuring the probability distribution of the intergalactic IGM and could constrain the locations of the cosmic baryons.

Recently, [Yang & Zhang \(2016\)](#) showed that the average host galaxy DM and cosmological parameters including the matter density and baryonic density can be independently inferred from the slope of the first derivative of the $DM_E - z$ relation. DM_E is the DM obtained after subtracting the Galactic contribution from the observed DM. This method requires a sample of FRBs for which DM and z are measured and a Markov Chain Monte Carlo (MCMC) fit can be applied to extract the DM_{host} and cosmological parameters using the slope ($\bar{\beta}$) of the DM_E versus z relation, and the mean values of DM_E and z of the sample. They define the two quantities (see equations (5) and (6) of [Yang & Zhang 2016](#)) as

$$\alpha(z) \equiv \frac{d \ln \langle DM_{\text{IGM}} \rangle}{d \ln z} \propto f(z, \Omega_m, \Omega_\Lambda) \quad (3)$$

and

$$\bar{\beta}(z) \equiv \frac{d \ln \langle DM_E \rangle}{d \ln z} \propto g(z, \langle DM_E \rangle, \langle DM_{\text{host}} \rangle). \quad (4)$$

At lower z , equation (4) can give an estimate for DM_{host} using measured values of $\bar{\beta}$ and z . At higher redshifts, $\langle DM_E \rangle \gg \langle DM_{\text{host}} \rangle$ and $\alpha(z) \simeq \bar{\beta}$, hence measuring $\bar{\beta}$ can give estimates for Ω_m . Since this method does not assume anything about the host galaxy DM, it can place constraints on some of the progenitor models.

Previously, [Zhou *et al.* \(2014\)](#) demonstrated that if sufficient FRBs (few tens) are detected in a narrow redshift interval ($\Delta z \sim 0.05$), then FRBs could help constrain the dimensionless parameter w which characterizes the equation of state of dark energy with pressure p and the dark energy density ρ ,

$$w = \frac{p}{\rho}. \quad (5)$$

They assume events with host galaxy DM less than $100 \text{ cm}^{-3} \text{ pc}$. For a sample of 1000 FRBs with known z , DM can be estimated. They performed a χ^2 statistic and compared the data from SNe Ia (solid yellow lines), baryon acoustic oscillations data obtained from Sloan Digital Sky Survey to estimate w .

[Wei *et al.* \(2015\)](#) also proposed that FRBs can be used to test the accuracy of Einstein's Equivalence Principle using the time delays caused by the gravitational potential of the Milky Way. [Bonetti *et al.* \(2017\)](#) analysed the time delay between different frequencies for FRBs whose redshifts are measured and placed upper limits on the rest mass of the photon. [Bonetti *et al.* \(2017\)](#)

estimated the rest mass to be $m_\gamma < 1.77 \times 10^{44} \text{ kg}$ for FRB 121102 at $z = 0.193$.

9. Summary

These millisecond duration and extremely bright radio bursts are opening up new and exciting ways to explore the Universe. Currently, 23 FRBs have been published which have been discovered with a wide range of telescopes (Parkes, Arecibo, GBT, ASKAP, Molonglo) between 800–2 GHz. Only one of these is a repeating source within a host galaxy at a redshift of 0.19 and the repeat pulses have been detected at a frequency up to 5 GHz. All of these FRBs have DMs well in excess of the expected contribution from the free electrons in the Milky Way and range between $266\text{--}1629 \text{ cm}^{-3} \text{ pc}$. It is still not conclusive if the dominant source of scattering is the IGM or the host galaxy as we have no information about the host galaxy for most of these sources and the theoretical scattering models for IGM have little observational evidence and are therefore dependent on a number of assumptions about the IGM properties. Future identifications of host galaxies and their observations can help up constrain the DM contribution due to the IGM and the IGM scattering models. FRBs may prove to be an excellent tool for understanding the properties of the IGM to significant redshifts. In addition, FRBs could serve as very useful cosmological tools and can help us in finding the missing baryons, in constraining the cosmological parameters, etc.

To study FRBs as a population, we need a larger sample. Given the relatively high all-sky rate of FRBs (1100–7000 FRBs per day per sky), a telescope with a large field-of-view, a large amount of time on sky, and high sensitivity would be able to find a large number of FRBs. In addition to the existing telescopes, a number of new powerful radio telescopes will begin searching for these highly dispersed bursts in the near future which are predicting much higher detection rates. For example, the Canadian Hydrogen Intensity Mapping Experiment telescope (CHIME; Newburgh *et al.*, 2014) is expecting to detect a few FRBs per day ([Rajwade *et al.* 2017](#); [Connor *et al.* 2017](#)). Also, precursor telescopes for the Square Kilometre Array (SKA) such the Australia SKA Pathfinder (ASKAP), MeerKAT, the Molonglo radio telescope (UTMOST), Five hundred meter Aperture Spherical Telescope (FAST) will enable us to find a larger sample of FRBs. Going forward, follow-up for FRBs and detailed statistical studies of the FRB population will be important to

place further constraints on progenitor models and eventually to have a better understanding of FRBs. Although many questions remain to be answered after a decade of research, overall FRBs have the potential to help answer some of the most fundamental questions in astrophysics. We look forward to the coming 5–10 years in which many of these issues can be resolved and explored via the discovery space that is about to be opened up by instruments such as ASKAP, CHIME and FAST.

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