A Decade of Fast Radio Bursts

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November 2, 2018

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Abstract

Modern astrophysics is undergoing a revolution. As detector technology has advanced, and astronomers have been able to study the sky with finer temporal detail, a rich diversity of sources which vary on timescales from years down to a few nanoseconds has been found. Among these are Fast Radio Bursts, with pulses of millisecond duration and anomalously high dispersion compared to Galactic pulsars, first seen a decade ago. Since then, a new research community is actively working on a variety of experiments and developing models to explain this new phenomenon, and devising ways to use them as astrophysical tools. In this article, I describe how astronomers have reached this point, review the highlights from the first decade of research in this field, give some current breaking news, and look ahead to what might be expected in the next few years.

Astronomers have long predicted the existence of short-duration pulses that might be present in high-time resolution surveys of the radio sky\textsuperscript{1}. In 2007, we published the first such example — a bright, highly dispersed pulse lasting 15 ms and of astrophysical but unknown origin\textsuperscript{2}. A decade on, with over 60 further examples\textsuperscript{3} of what are now known as Fast Radio Bursts (FRBs), astronomers are now probing a population within the landscape of transient phenomena. We now think about the Universe both in terms of sources we see from epoch to epoch, and transients like FRBs which provide an ever-changing landscape rich in possibilities for future study.

The story of FRBs can be traced back to the serendipitous discovery of pulsars by Jocelyn Bell and Anthony Hewish in 1967\textsuperscript{4}. Pulsars are characterized by the short duration (few 10s of ms) pulses which are extremely regularly spaced. Today, with over 2600 pulsars known\textsuperscript{5}, the currently accepted picture of a pulsar is that it is a rapidly rotating highly magnetized neutron star which formed from the collapsed core of a normal star after it underwent a supernova explosion. The pulses detected on Earth are caused by the rotation of the magnetic field which sweeps across our line of sight in much the same way as a lighthouse. The first pulsars were found through their individual pulses, but subsequent searches relied on the improved sensitivity that comes from Fourier analyses of long data streams\textsuperscript{6}.

Among the first pulsars to be discovered was PSR B0531+21 in the Crab nebula\textsuperscript{7} which was originally seen through the emission of exceptionally bright individual pulses. The Crab and other energetic pulsars are now known to emit what are now known as giant pulses with a rate that follows a power-law distribution of amplitudes\textsuperscript{8}. Crab-like giant pulses could only be seen in the nearest galaxies using the largest radio telescopes\textsuperscript{9}.

The promise of detecting pulses from energetic sources inspired a number of searches over the years. Following Hawking’s prediction in 1974\textsuperscript{10} that black holes formed early in the Universe’s history would
actually be evaporating today, Rees suggested them as a potential population of sources emitting bright radio pulses\cite{11}. Colgate also predicted radio pulses produced during supernova explosions\cite{12}. Motivated by these predictions, Phinney and Taylor carried out a search for bursts in data taken with the Arecibo radio telescope\cite{13}. Although unsuccessful, this search placed the first constraints on the rates of bursting radio sources in the Universe. Other searches have been carried out over the intervening years but, despite unconfirmed claims of pulses from the giant elliptical galaxy M87\cite{14}, no further events were found\cite{15}.

By the end of the 1990s, as telescope instrumentation and the availability of high-speed computing resources improved, the interest in searching for radio pulses was renewed\cite{16,17}. McLaughlin et al.\cite{18} applied the single-pulse search techniques to a large-scale survey with the Parkes radio telescope and found a new population of sporadically emitting sources known as Rotating Radio Transients (RRATs). While RRATs were quickly identified with Galactic neutron stars, during further searches of data collected in a survey of the Magellanic clouds, we serendipitously discovered a bright and highly anomalous new type of pulse\cite{2}.

Fig. 1 shows the pulse we found (now known as the Lorimer burst) in terms of radio frequency versus arrival time for a band spanning 288 MHz centred around 1374 MHz. Due to the frequency-dependent refractive index of the ionized interstellar medium, the highest frequency components of the signal travel faster than their lower frequency counterparts and arrive earlier. The signature of this effect is the inverse quadratic delay of the pulse with observing frequency\cite{4}. The total delay across an observing band is proportional to the dispersion measure

\[
DM = \int_0^d n_e dl.
\]

Here \(d\) is the distance to the source and \(n_e\) is the number of electrons per unit volume along the line of sight. It is also noticeable that the pulse gets broader towards the lower frequencies. This is also a hallmark that is expected for a pulse propagating through a turbulent medium and is well-known from studies of pulsars. Using models for the electron density\cite{19}, astronomers routinely estimate the distance to pulsars and RRATs from their observed DM values. Applying the same technique to the Lorimer burst, it is immediately apparent that the delay is too large (by about an order of magnitude) to be attributed to free electrons in the Milky Way. In addition, since the location of the pulse is about three degrees south of the Small Magellanic Cloud, we concluded that the source was located well beyond the Milky Way and Magellanic Clouds. Despite almost 100 hours of follow-up observations, no further pulses were found. Making parallels with gamma-ray bursts we proposed that this event was a prototype of a new class of astrophysical transients, and that the rate of similar bright bursts over the sky could be at least as large as a few hundred per day.

In spite of a great deal of effort that went into trying to identify further examples in other archival data sets, the small fields of view of most radio telescopes and the short duration of the bursts meant that subsequent detections were not immediately forthcoming. Bursts were detected that were clearly of terrestrial origin (referred to as Perytons\cite{20}), that have subsequently been traced to emission from microwave ovens\cite{21}. In 2012, however, a second convincing burst of astrophysical origin from a different sky location was found in Parkes data taken of a survey of the Milky Way\cite{22}. Like the Lorimer burst, its DM was larger than that expected from electrons in the Milky Way and was likely much further away. For many researchers, a game-changing discovery in the field came in 2013 with the announcement of four more bursts by Thornton et al.\cite{23} which clearly revealed a population of highly dispersed anomalous pulses. At this point the convention of naming the phenomenon Fast Radio Bursts (FRBs) began. The designation for each FRB followed that of the gamma-ray bursts as year, month and day of its arrival at the telescope. For example, the FRB discovered on February 20, 2011 is called FRB 110220. Presently over 60 FRBs are known, and an up-to-date list of source parameters can be found online\cite{3}. In addition to further discoveries at Parkes, FRBs have also been found at Arecibo\cite{24}, Green Bank\cite{25}, Molonglo\cite{26,27}, ASKAP
Figure 1: Waterfall plot showing radio frequency versus time (lower panel) for the original FRB 010724 in the main beam of the telescope. The upper panel shows the de-dispersed pulse after appropriately delaying the filterbank channels to account for the inverse frequency squared behaviour seen below. Also evident in these figures is the offset level of the baseline noise prior and following the pulse. This is due to nature of the integrating circuit employed in the single-bit digitizers by this extremely bright pulse and was not shown in the original discovery paper [2]. Figure credit: Evan Keane.
Figure 2: Dispersion measure (DM) versus Galactic latitude ($b$) showing pulsars (small dots) and Fast Radio Bursts (larger blobs). The clear $1/\sin(b)$ dependence of DM with $b$ for pulsars as a result of the finite size of the electron layer is evident. Also seen are faint excesses of pulsars in the Large and Small Magellanic clouds. For FRBs, whose DMs are not dominated by Galactic electrons, no such trend is seen.

– the Australian Square Kilometre Array Pathfinder\[28, 29\] and, most recently the Canadian HI Intensity Mapping Experiment (CHIME)\[30\]. As shown in Fig. 2, the anomalously high dispersion of this sample of FRBs is a defining trait, clearly representative of a different population compared to Galactic pulsars and RRATs.

In an analogous way to how distances to pulsars are estimated from their DMs, which make use of a model for the free electrons in the Galaxy\[19\], redshifts of FRBs, $z$, can be estimated from a model of the distribution of electrons which turns out to be dominated by those spanning intergalactic distances. As a very crude rule of thumb\[31\], $z \sim (\text{DM}/1000 \text{ cm}^{-3} \text{ pc})$, so for typical FRBs with DMs in the range 200–2600 cm$^{-3}$ pc, we infer redshifts in the range $0.2 < z < 2.6$. We stress that this calculation uses an estimate of the redshift rather than a direct measurement which has up to now only been possible for one source, FRB 121102, discussed further below. However, with these caveats in mind, for a canonical FRB with DM = 1000 cm$^{-3}$ pc with a peak flux density of a jansky and a width of 5 ms, one can infer a co-moving
distance of 3 Gpc and equivalent energy release of $10^{32}$ joules\textsuperscript{[23]}. For reference, the Sun emits $10^{26}$ W, so this corresponds to the amount of energy released by the Sun in two weeks! Although this seems like a lot, a typical Gamma-Ray Burst releases something like $10^{45}$ joules — more energy than the Sun will emit in its ten billion year projected lifetime!

By the beginning of 2016, due to the lack of repeat pulses among FRBs known at the time, in spite of hundreds of hours of follow-up time\textsuperscript{[2]}\textsuperscript{[23]}, a suspicion among many researchers was that FRBs do not repeat and are likely one-time events. FRB 121102, originally found at Arecibo\textsuperscript{[24]}, has now been observed to repeat on multiple occasions\textsuperscript{[32]}\textsuperscript{[33]}\textsuperscript{[34]}\textsuperscript{[35]}. Individual pulses are quite variable in nature. A major implication of this discovery, however, is that for FRB 121102, whatever is producing these bursts, it cannot be catastrophic in nature. Models involving one-off explosions, or stellar mergers, for this source at least are ruled out.

Further constraints on the nature of FRB 121102 have now been found thanks to the precise localization of the source in 2017 using the Karl Jansky Very Large Array\textsuperscript{[36]}, and the measurement of a significant amount of polarization in the source by the Arecibo telescope\textsuperscript{[37]}. The positional determination\textsuperscript{[36]} allowed the unambiguous association of FRB 121102 with a low-metallicity star-forming dwarf galaxy at redshift $z = 0.192$\textsuperscript{[38]}. This is the first, and currently only, identification of a counterpart and the direct measurement of distance to an FRB. The luminosity distance corresponding to this redshift is 972 Mpc. The implied isotropic energy release of individual bursts is variable and ranges between $10^{30}$ and $10^{33}$ joules\textsuperscript{[34]}.

Further radio observations using the European Very Long Baseline Interferometry Network and Arecibo\textsuperscript{[39]} provide compelling evidence for an association of FRB 121102 with a persistent radio source within this dwarf galaxy. This could be explained as being a signature of the emission from either the nucleus of the galaxy, or of a young pulsar energizing a supernova remnant therein\textsuperscript{[39]}\textsuperscript{[40]}. Subsequent polarization measurements presented by Michilli et al.\textsuperscript{[37]} show that the radio emission is almost entirely linearly polarized and the amount of Faraday rotation of the electromagnetic signal is variable, but extremely high: in the range 130,000–150,000 radians per square metre. Such large rotation measures are only observed in the extremely highly magnetized environments found close to supermassive black holes, such as Sagittarius A* at the center of our Galaxy\textsuperscript{[41]}.

FRB 121102 is presently unique in that it shows multiple pulses which are sporadic in nature. Unlike the case for pulsars and RRATs, there is no discernable periodicity. The shortest separation between bursts currently observed is 34 ms\textsuperscript{[33]}. Do all FRBs repeat? While we cannot definitively rule out the existence of repeat bursts on timescales of years, there is now growing evidence that burst rates of the kind only seen in FRB 121102 are the exception, rather than the rule. At the time of writing, most FRBs have been observed for hundreds of hours, without any evidence for repeat pulses. A recent analysis\textsuperscript{[42]} based on a sample of 21 FRBs found at Parkes, if all FRBs are like 121102, finds the probability of non-detections in the sample is less than 0.1%. A novel feature of the initial survey by ASKAP\textsuperscript{[28]}\textsuperscript{[29]} is that the same fields on the sky are repeatedly observed. Each of the 20 FRBs found in this survey has typically hundreds of hours of follow-up time with comparable sensitivity. An analysis of these non-detections\textsuperscript{[29]} also concludes that it is unlikely that they have amplitude distributions similar to FRB 121102. Although further constraints from other surveys and more sensitive telescopes will be more useful, it is becoming increasingly likely that, much like gamma-ray bursts, that there are two distinct classes of FRBs. In what follows, we will proceed under the assumption that this is the case, i.e. that there are both repeating FRBs and one-time FRBs.

So far, I have talked very little about what FRBs could be. This is largely because the nature of the sources is still unclear. A stringent constraint on the emission mechanism can be made by noting that, for a pulse with peak flux density $S_{\text{peak}}$, and width $W$ at a distance $d$ from the Earth, observing a some frequency $f$, the equivalent temperature of a blackbody source of the same isotropic luminosity, i.e., the brightness
\[ T_b = \left( \frac{S_{\text{peak}}}{2\pi k} \right) \left( \frac{fW}{d} \right)^2 , \]

where \( k \) is Boltzmann’s constant. Inserting the measured values now available for FRB 121102, we find \( T_b \sim 10^{35} \text{K} \) which clearly implies a coherent non-thermal radiation mechanism that all explanations summarized below must satisfy.

Very much like in the early days of gamma-ray burst astrophysics, there are currently more theories for the emission mechanisms than actual FRBs known. Those put forward thus far broadly into three main categories: extraterrestrial, Galactic and extragalactic. The first of these, that FRBs represent some sort of message from extra-terrestrial civilizations, can be largely discounted by the preponderance of them over the whole sky. Similar arguments were made following the discovery of pulsars. Any source of FRBs that originates in the second category, i.e. as natural sources from within our Galaxy, have to find a way of explaining the extremely high DMs observed for FRBs when compared with the pulsar population that is now well studied. Clearly FRB 121102 is inconsistent with a Galactic origin. Attempts to explain the rest of the FRBs as coming from anomalously high dispersion produced by Galactic flare stars, remains less attractive due to fact that the high implied plasma densities would not result in an inverse frequency squared dispersion.

Within the extragalactic category, theories consistent with the observed energetics involve compact objects (i.e. black holes, neutron stars, strange stars and white dwarfs) which are necessary, from light-travel-time considerations, to explain the short duration of the pulses. Among the models currently suggested are: collapsing neutron stars forming black holes, coalescing neutron star binaries, coalescing neutron star—black hole binaries, coalescing white dwarf binaries, primordial black holes falling into neutron stars, evaporating black holes, giant pulses from young neutron stars, nascent and highly energetic magnetars, white holes. While these scenarios involve compact stars, non-stellar options involving cosmic strings, large-scale defects in the structure of spacetime thought to have been formed in early Universe, have also been proposed. Such theories, while in principle still viable, do need to be further developed so that they can make concrete and testable observational predictions.

Regardless of the origin of FRBs, predictions for ongoing and future experiments can be made by relatively simple modeling of them as a cosmological population. To demonstrate how a self-consistent model can be set up, one can mimic the \( S_{\text{peak}}-\text{DM} \) distribution seen in the Parkes pulsars using a very simple Monte Carlo simulation. In this model, synthetic FRBs are uniformly distributed in co-moving volume out to \( z = 2.5 \). A redshift is computed for each one and a DM is assigned which assumes a contribution of 25 cm\(^{-3}\) pc from the Milky Way, 1000 cm\(^{-3}\) pc from the intergalactic medium, and 150 cm\(^{-3}\) pc from the host. A radio luminosity is chosen from a normal distribution with a mean of 180 Jy Gpc\(^2\) and standard deviation of 100 Jy Gpc\(^2\). The flux density of each FRB is then computed. To simulate the uncertain position of each FRB within the Parkes telescope beam, these fluxes are additionally multiplied by a dithering factor from a Gaussian with full-width half maximum of 11 arcminutes. The result of this simulation is shown as the background of small points in Fig. 3. This simple procedure demonstrates that the sample requires a distribution of luminosities, and that FRBs are unlikely to be standard candles. More detailed analyses can be found elsewhere. With larger sample sizes and more detailed modeling in the future, it should be possible to better constrain the luminosity distribution and spatial distribution of the population.

I have summarized the discovery and salient properties of a population of mysterious radio bursts of currently unknown origin that appear to originate from random locations on the sky. Perhaps the most remarkable thing about FRBs is their inferred rate of occurrence. Based on the fields of view and time spent in surveys to date, current estimates of their all-sky rates range between \( 10^3 \) and \( 10^4 \) FRBs per sky
Figure 3: Peak flux density versus dispersion measure (DM) for observed (large stars) and simulated (dots) FRBs. The simulation assumes FRBs are uniformly distributed in co-moving volume with a Gaussian luminosity function (see text). Although the simulated events span the DM and flux densities of the observed sample, refinements to the model will be required to produce the correct proportion of events as a function of DM and flux density. More sophisticated simulations are now being carried out\cite{62, 63}. 
per day\textsuperscript{23} \textsuperscript{64}. Expressed in another way, somewhere over the sky, an FRB goes off every 30 seconds! Although all the models we reviewed previously can be tuned to accommodate this rate, many of them could be ruled out if we knew the distance scale for the FRBs and, hence, their rate per unit volume in the Universe. To emphasize the extent of the problem, FRBs are currently not too far below the most violent known explosions in the Universe – supernovae, which occur somewhere in the visible universe at a rate of about one per second. If we are missing a significant fraction of faint FRBs, or if many of them are not beamed towards us, the rate that we infer could be as high or even higher than the supernova rate. If, as it seems likely, there are multiple sub-populations of FRBs (e.g. repeating and non-repeating sources), what are the relative rates of these? Only through the discovery of a larger sample of these objects will we be able to answer these questions.

Currently, new FRBs continue to be found with existing instrumentation. ASKAP is making great inroads into the low DM (100–1000 cm\textsuperscript{-3} pc) population, with over 20 discoveries so far\textsuperscript{29}. ASKAP has also found the first FRB that directly probes the line of sight of a galaxy cluster. In a 300-hr survey with ASKAP, Agarwal et al.\textsuperscript{65} have found one bright FRB that probes the ionized medium of the Virgo cluster. Further examples of such pulses could be found by dedicated searches of nearby galaxy clusters\textsuperscript{66}. Very recently, CHIME has begun operations in the 400–800 MHz frequency band and has already found several FRBs, including some that are visible at frequencies as low as 400 MHz\textsuperscript{30}.

The next decade is set to be very promising for FRB hunting\textsuperscript{67}. New instruments coming online at Arecibo, Green Bank, and elsewhere promise to find more of these enigmatic sources. Predictions for CHIME are extremely promising, with rates of up to dozens of sources per day being possible\textsuperscript{68}! A new giant telescope in China – the Five-Hundred-Meter Aperture Spherical Telescope (FAST) – also recently completed, will have unprecedented sensitivity for faint and distant FRBs\textsuperscript{69}. At the time of writing, FAST is about to begin surveys with a 19-beam system, while plans are underway to upgrade Arecibo’s throughput to 40 beams. Predictions for FAST and Arecibo FRBs using the simulations described above suggest that they could see sources out to redshift of 5 with DMs approaching 10,000 cm\textsuperscript{-3} pc.

A new radio telescope in South Africa, MeerKAT will soon begin scanning the skies for FRBs\textsuperscript{70} and an optical partner, known as MeerLICHT\textsuperscript{71} will simultaneously observe them at optical wavelengths. Such an experiment would probe the optical transient sky in an entirely new way, and place further constraints on the FRB emission mechanism\textsuperscript{72}. MeerKAT is a precursor to the next generation radio telescope known as the Square Kilometer Array (SKA) which, upon its completion in the mid 2020s\textsuperscript{73}, would be able to locate and study FRBs to unprecedented precision. There will be no doubt many surprises in store as we enter the second decade of study of FRBs. I predict that by 2030 FRBs will become standard tools to study the large-scale structure and magnetoionic content of the cosmos. Only time will tell, of course, but if the first ten years is anything to go by, FRBs still have plenty of surprises in store for astrophysics in the next decade.

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