The discovery and scientific potential of fast radio bursts

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BACKGROUND: Fast radio bursts (FRBs) are broadband, millisecond-duration bursts of radio emission visible at cosmological distances. As FRBs traverse the intergalactic medium, their radiation is slightly delayed by the presence of free electrons in a frequency-dependent manner. When these delays are combined with cosmological models of the distribution of baryons in the Universe, they can infer distances. The first FRB, the Lorimer Burst, was discovered in 2007. Although its radio brightness was similar to that of radio pulsars (neutron stars) in the Milky Way, its inferred distance was a million times greater, indicative of a new class of object.

Instrumental and computational advances made FRB discovery routine by the mid-2010s, and there are many thousands of bursts known from more than 600 unique sources. Some FRBs arise from sources that produce multiple bursts, separated by anything from seconds to months, and these are known as “repeaters.” However, the majority of FRB sources have never been seen to repeat.

Because most of the baryonic (normal) matter in the Universe is ionized, FRBs can constrain the total baryonic content of the Universe. The discovery of FRBs raised two scientific questions: (i) what produces them? and (ii) what can they tell us about the Universe?

ADVANCES: The early FRBs were discovered using single radio dishes with limited spatial resolution. These instruments established that FRBs might be detectable to redshifts corresponding to when the Universe was only half its current age. However, they were unable to localize any FRBs to their host galaxies, so their true distances remained uncertain. In 2016, the first repeating FRB was discovered, which allowed follow-up observations using radio interferometers with better spatial resolution. These showed that the repeating source is situated in a small, low-metallicity dwarf galaxy at a distance confirming their cosmological nature and near a persistent source of radio emission. The localization of the repeater thus demonstrated that the luminosities of FRBs were extremely high.

Improved instrumentation greatly expanded both the number of observed FRBs and the number with identified host galaxies. Localizations of repeaters determined numerous host galaxies and showed that repeating FRBs are likely to be associated with young, highly magnetic neutron stars (magnetars). Some repeaters appear to have cyclic activity windows, which is consistent with an orbit, or possibly a precession, of the source. The degree of linear polarization of repeaters is strongly frequency dependent, indicating that they are often located in highly magnetic, ionized environments.

Further developments in instrumentation enabled the localization of many nonrepeating FRBs. Combining all the known FRB host galaxies led to a measurement of the baryonic content of the Universe. More than 1000 FRBs were detected from a single repeater but with no underlying periodicity. In 2020, an FRB was observed from a magnetar within the Milky Way.

OUTLOOK: The diversity of FRBs continues to expand. One FRB had emission extended over several seconds, punctuated by bursts with a 217-ms periodicity. Others showed weaker evidence for faster periodicities, at 2.8 and 10.7 ms, which could be linked to the rotation period of the neutron stars thought to produce them. The initial 12 orders of magnitude in luminosity between the early FRBs and pulsars in the Milky Way is being closed by observations of fainter FRBs. The nature of the sources and the emission mechanism remains unclear. It is possible that there are multiple ways of producing FRBs, including from unusual locations such as millisecond pulsars in globular clusters.

New instruments are currently being constructed and commissioned that will have increased sensitivity. These will also localize many more FRBs to their host galaxies, increasing the utility of FRBs in cosmology.

Timeline of some important breakthroughs in FRBs. The blue graph indicates the cumulative number of FRBs detected (~800, including some bursts from repeaters). Source: HeRTA: FRBSTATS online catalog.
Fast radio bursts (FRBs) are millisecond-time-scale bursts of coherent radio emission that are luminous enough to be detectable at cosmological distances. In this Review, I describe the discovery of FRBs, subsequent advances in understanding them, and future prospects. Thousands of potentially observable FRBs reach Earth every day, which likely originate from highly magnetic and/or rapidly rotating neutron stars in the distant Universe. Some FRBs repeat, with this subclass often occurring in highly magnetic environments. Two repeating FRBs exhibit cyclic activity windows, consistent with an orbital period. One nearby FRB was emitted by a Galactic magnetar during an x-ray outburst. The host galaxies of some FRBs have been located, providing information about the host environments and the total baryonic content of the Universe.

The study of radio pulsars has been advanced by discoveries of unusual objects, usually in large-scale surveys (2, 10, 11). A new class of pulsar-like objects, the rotating radio transients (RRATs) were discovered in 2006 using the Parkes Multibeam Receiver (12), a 13-pixel radio camera that was used in multiple pulsar surveys (6, 7, 13, 14). RRATs (15) were initially interpreted as an atypical type of pulsar that only rarely emitted pulses, albeit always in phase with a neutron star’s rotation period. This was unlike radio pulsars, which usually emitted regular pulsations with each rotation. In 2007, searches were underway to find more examples of RRATs (16–18).

Like pulsars, RRATs exhibit a radio frequency-dependent delay that appears as a sweep on the radio receiver. This arises because radio waves travel slightly slower in the ionized interstellar medium than the speed of light in a vacuum (c). The speed is determined by the radio frequency (ν) and the density of free electrons (Fig. 1A). By time a broadband radio pulse arrives at Earth, this frequency-dependent delay leads to a well-defined sweep in which the higher radio frequencies arrive before the lower ones (shown in Fig. 1C for PSR J1707–4053). A radio pulse’s dispersion measure, DM = ∫_0^L n_e dL, is the integrated column density of free electrons along the line of sight, where n_e is the local free electron density in cubic centimeters, L is the distance to the source in parsecs (pc), and DM is the dispersion measure expressed as parsecs per cubic centimeter. The difference in the arrival times (t_2 − t_1) between two radio waves of frequencies ν_2 and ν_1 is approximately as follows (19):

\[
t_2 - t_1 \approx 4.15 \left[ \frac{1}{\nu_2^2} - \frac{1}{\nu_1^2} \right] \text{DM \, ms}
\]

where the radio frequency is expressed in gigahertz. The measured DM of a source, combined with a free electron model, can be used as a proxy for distance within the Galaxy (20, 21) and for cosmological distances (22). Although it greatly complicates radio pulsar instrumentation and analysis, pulse dispersion helps observers distinguish celestial sources from local radio interference, and is ultimately the effect that allows FRBs to have cosmological applications.

D. R. Lorimer and undergraduate student D. J. Narkevic searched for RRATs in an archival multibeam pulsar survey of the Small Magellanic Cloud (SMC), a nearby dwarf galaxy, using the Parkes 64-m telescope. Narkevic’s initial analysis had detected a total of two putative RRATs in the whole SMC survey. They both appeared at exactly the same time with DM ~375 pc cm^{-3} in two adjacent beams of the 13-beam receiver, suggesting that either a very bright source was illuminating the sidelobes of multiple beams or there was an unusual form of radio interference (Fig. 1B).

I was observing at the Parkes telescope on an unrelated project with Lorimer and became involved in diagnosing the putative dispersed radio source. We extracted the relevant burst data and displayed them as waterfall plots, which show the pulse energy as a function of both time and frequency (23, 24). We found that the source had a dispersion sweep similar to those of pulsars, with evidence of radio frequency-dependent multipath interstellar scattering (which scales as ν^{-4}), as is often seen in observations of pulsars (25) (Fig. 1, D and E). Further investigation showed that the burst had saturated the receiver in the beam closest to the source’s location (beam 6 in Fig. 1B), which have limited dynamic range, causing an algorithm designed to remove interference to replace the burst with synthetic data. If the instrument had not been sensitive to strong signals in multiple beams, then the burst would never have been found. Disabling the interference rejection algorithm and reprocessing the archived data showed that the burst was >100 times the survey’s detection threshold, with an estimated flux density of 30 jansky (Jy) (Fig. 1, D and E). The burst was bright enough to be visible in four of the 13 beams (26, 27).

The estimated source distance placed it well beyond the SMC (the target of the survey); it appeared to be at cosmological distance (I). In the voids between galaxies, free electron densities (22) are ~1 m^{-3}. This makes the source distance equivalent to ~1 Mpc for each 1 pc cm^{-3} of the DM after removing the Milky Way foreground. Thus, the DM of ~375 pc cm^{-3} indicated a distance of ~1 Gpc; for comparison, the Milky Way is ~30 kpc across and the SMC is at a distance of ~60 kpc. To explain the observed brightness at such a distance, the source

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would have to be about a trillion times more luminous than any known pulsar. Alternatively, the source could have been enshrouded in a highly ionized plasma in its host environment, leading to a spurious distance estimate. There is a subclass of high-magnetic-field and/or short-period pulsars that are known to occasionally emit highly energetic radio pulses, which might have been linked to the burst. The Crab Pulsar, a young and highly magnetized neutron star, occasionally produces these giant pulses, individual radio flashes that can be much brighter than the mean energy of its average pulse. However, even the brightest Crab Pulsar giant pulses were about a trillion times less energetic than the putative burst (Fig. 3). The implied radio energy emitted in the 5-ms-duration burst was similar to all the power the Sun emits over a month.

The burst was well above the survey detection threshold. In extragalactic surveys, a homogeneous isotropic cosmological population follows the relation $d \log N/d \log S = -3/2$, where $N$ is the number of sources above a flux density $S$. This arises because the volume surveyed expands as the distance $D^3$, whereas each object's flux density follows the inverse square law $D^{-2}$. For every Lorimer Burst, there should be many (perhaps dozens) of fainter bursts present in the survey data. There did not appear to be any. [A FRB search (28) found another FRB in the same dataset, with a DM of 1187 pc cm$^{-3}$, but that was only identified years later.]

If the source repeated, then it would provide more confidence in its celestial origin, but 40 hours of follow-up observations at Parkes saw nothing (1). It appeared that the burst was either (i) a one-off hyperluminous flash of radio waves from the distant Universe (Fig. 3). The implied radio energy emitted in the 5-ms-duration burst was similar to all the power the Sun emits over a month. The cross indicates the inferred burst position (1). (C) Observed dispersion sweep of the pulsar PSR J1707–4053 with DM = 360 pc cm$^{-3}$ and its de-dispersed pulse profile (inset) (125). (D and E) Dispersion sweep and integrated pulse profile (inset) of the Lorimer burst at DM = 375 pc cm$^{-3}$ in sidelobe beam 13 (D) and beam 6 (E). The dip in flux after the burst in beam 6 is an instrumental artifact caused by saturation. (F to K) Inferred evolution of the Lorimer Burst’s dispersion over cosmic time. $T_0$ is the time of emission.
Lorimer Burst had potential for use as a cosmological probe. The DM contains information on the number of free electrons along its path. Most of the Universe’s baryonic (normal atomic) mass is not in galaxies, but between them in the intergalactic medium (IGM). The bulk of the IGM mass is in hydrogen and helium, which do not retain their electrons because they are ionized by ultraviolet light. An FRB can therefore act as a free electron (and hence baryon) counter between the host galaxy and Earth (Fig. 1, F to K). Localized FRBs could potentially constrain the total mass of IGM, a quantity with controversial measurements using other methods (29).

**The hunt for more FRBs**

Attempts were made to find more bursts, both from existing archival data and by initiating surveys that specifically targeted FRBs. However, none of the early efforts was successful. Many groups searched archival data, finding some additional RRATs (18, 30), but no events similar to the Lorimer Burst were found. Surveys specifically designed to find new bursts (31, 32) also initially did not detect any. It was discovered that the Parkes Radio Telescope receiver was often struck by quasidispersed radio pulses that were present in all 13 beams of the multibeam receiver, some of which had dispersion similar to the Lorimer Burst (33). These were shown to be caused by a micro-wave oven ~100 m from the Parkes dish (34), raising further doubts. Was the Lorimer Burst just a similar form of radio interference?

In 2012, another search of the Parkes Multi-beam Pulsar Survey found a potential Lorimer Burst–like signal (35) with a DM of 745 pc cm$^{-3}$, although it was uncertain whether it originated outside of the Galaxy (36). The celestial and cosmological nature of these dispersive radio signals was therefore uncertain.

**2013: A cosmological population**

In 2008, three pulsar and radio burst surveys commenced at Parkes, called the High Time Resolution Universe (HTRU) surveys (37). These used multibeam anti-coincidence detection methods (38) that proved effective at removing terrestrial near-field interference. In 2013, one of the HTRU surveys found four radio bursts (39), the brightest of which had a DM almost three times that of the Lorimer Burst that followed the same frequency. This demonstrated that fainter and higher-dispersion (more distant) bursts existed, implying that the Lorimer Burst was part of a cosmological population. The term “fast radio burst” and the acronym FRB were coined at that time. A system of nomenclature was adopted, designating each burst FRB followed by numerals indicating the date it

**Implications of the Lorimer Burst**

The apparent luminosity of the Lorimer Burst was very high, but there were few clues as to what may have caused it. There was only an upper limit (≤5 ms) on the intrinsic width of the burst due to a combination of instrumental broadening and radio wave scattering. Requiring the emission region to be causally connected (within 5 ms of travel time at the speed of light) set an upper limit on its size of ≤1500 km. Such distance scales are consistent with the dimensions of the rotating magnetic fields seen in rapidly rotating neutron stars, shocks from explosions emanating from relativistic objects, or collisions between neutron stars and other compact objects (neutron stars or stellar-mass black holes).

Radio telescopes observe a small fraction of the sky, so initial estimates of the FRB event rate were hundreds per day for FRBs as bright as the Lorimer Burst (1) and 10,000 d$^{-1}$ for fainter bursts that were still above the detection limit of large radio dishes. The implied rate in a given cosmological volume was similar to that of supernovae: about once every few decades in a normal galaxy.

If its origin could be determined, then the Lorimer Burst had potential for use as a cosmological probe. The DM contains information on the number of free electrons along its path. Most of the Universe’s baryonic (normal atomic) mass is not in galaxies, but between them in the intergalactic medium (IGM). The bulk of the IGM mass is in hydrogen and helium, which do not retain their electrons because they are ionized by ultraviolet light. An FRB can therefore act as a free electron (and hence baryon) counter between the host galaxy and Earth (Fig. 1, F to K). Localized FRBs could potentially constrain the total mass of IGM, a quantity with controversial measurements using other methods (29).

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Fig. 3. Luminosity as a function of burst timescale for short-duration coherent radio emitters. The Lorimer Burst (green triangle) is a trillion times more energetic than radio pulsars (light green circles) and RRATs (orange crosses) within the Milky Way. Also shown are other one-off FRBs (magenta pentagons), repeating bursts from FRB 20121102A (light purple crosses) and FRB 20180916B (dark purple plus symbols), the repeating FRB 20200120E in a globular cluster of M81 (yellow diamonds), and radio bursts from the galactic magnetars SGR 1935+2154 (black squares) and XTE J1810–197 (blue stars). Nanosecond duration bursts from the Crab Pulsar (brown triangles) have similar brightness temperatures (the black body temperature that would produce equivalent brightness) to the most energetic FRBs. The sloped dotted gray lines indicate the brightness temperature, which is proportional to the specific intensity of a source. Luminosities and time scales are from (1, 76, 128).

occurred, similar to that used for for gamma-ray bursts. For example, FRB 110220 was detected on 20 February 2011 Universal Coordinated Time (UTC); it had a dispersion measure of 995 pc cm\(^{-3}\) (39). Models of extragalactic dispersion indicated that the sources could be at distances up to redshift \(z = 1\), when the Universe was half its current age.

2014–2017: Single-dish discoveries
Although the four additional FRBs were reassuring, they had also been discovered with the Parkes 64-m telescope. Was there something in its local environment that was mimicking dispersed pulses? This doubt was dispelled in 2014, when a team using the Arecibo 305-m dish in Puerto Rico (Fig. 2B) announced the detection of another FRB (40). FRB 121102 had a DM of 556 pc cm\(^{-3}\) and, like the Parkes examples, appeared to be far beyond the Milky Way. Another DM = 700 pc cm\(^{-3}\) FRB was found in archival data (41), and then a bright FRB was identified using the 100-m Green Bank Telescope (GBT) (42), which recorded full polarimetric information showing that the FRB had a polarization fraction of almost 50%. Changes in the position angle of the polarization as a function of frequency (known as Faraday rotation) were evident, indicating that the FRB source was probably immersed in a highly magnetized region within its host galaxy. Another five FRBs (43) were identified in the HTRU survey, including evidence that the bursts might have multiple components, and a DM as high as 1629 pc cm\(^{-3}\) was found. Other FRBs well above the detection threshold were also discovered using the Parkes 64-m telescope (44, 45).

Single-dish radio telescopes have poor spatial resolution (several square degrees), so none of these FRBs could be unambiguously associated with a host galaxy. A definitive demonstration that FRBs are at cosmological distances could potentially be made by using an interferometer, which has much better spatial resolution, to localize an FRB to a host galaxy (46). Without known distances or association at other wavelengths, it was difficult to constrain models of emission mechanisms or even be certain that FRBs were a cosmological population.

Early physical models
A catalog of theories for the emission mechanism of FRBs (47) listed more models than there were then known bursts. If FRBs are at cosmological distances, then their estimated radio energies are \(10^{36}\) to \(10^{40}\) ergs. This is about the same total energy as the Sun emits in a day to a month, but all in the radio band and all within a few milliseconds. Although this eliminates Sun-like stars as the source of FRBs, there are nevertheless many potential astrophysical sources. Accreting neutron stars often exhibit x-ray luminosities of \(10^{38}\) ergs s\(^{-1}\) and the Crab Pulsar releases its rotational kinetic energy at a rate of \(4 \times 10^{38}\) ergs s\(^{-1}\). Either could regularly emit a low-powered FRB without violating energy conservation.

Causality requires that the dimension \((d)\) of an FRB source must be \(d \leq 3c\delta t\), where \(c\) is the speed of light and \(\delta t\) is the duration of the FRB. For observed FRB time scales <1 ms, the dimension of the emission region had to be <300 km. This suggested compact objects such as neutron stars or black holes, or possibly relativistic shock waves, in close proximity to a source at similar scales. Hot extended plasmas emit incoherent radio emission because of the interaction of charged particles, with a spectrum and luminosity determined by their dimension and temperature. To reach the luminosities of FRBs in the available time scale would require an incoherent source to have an implausible temperature (~\(10^{40}\) K). Therefore, the FRB emission mechanism must be a coherent process, one in which \(N\) charged particles emit radio waves all in phase, producing \(N^2\) times the power of a single particle (48). Examples of coherent processes are (i) plasma emission involving the generation of Langmuir waves and subsequent conversion into waves at the plasma frequency, (ii) electron cyclotron maser emission, and (iii) pulsars. Of these, the pulsar emission mechanism is the least understood. Giant pulsars from the Crab Pulsar are thought to be caused by many nanosecond time-scale shots, each of which individually produces coherent emission that appear in quick succession, resulting in a giant pulse (49).

Early models for extragalactic FRBs could be assigned into two broad categories. In its first, some catastrophic explosion or other source-destructing event occurred, releasing a large amount of energy, some small fraction of which was converted into a coherent radio pulse. These are known as cataclysmic models. Examples include a neutron star–neutron star merger (50), a core-collapse gamma-ray burst or otherwise unusual (superluminous?) supernova explosion, or a neutron star that briefly exceeds its maximum stable mass before collapsing to a black hole (51). In these models, the FRB can...
never repeat, and many of the events are expected to be associated with star-forming galaxies, which have large numbers of massive stars and high supernova rates. Cataclysmic models invoking decelerating blast waves (52) predicted unresolved FRBs with radio bandwidths \( \delta v/v \sim 1 \), similar to the bandwidths of the receivers used in many radio telescopes, whereas models invoking the magnetospheres of relativistic objects could contain finer temporal and band-limited spectral features (49), as exhibited in the giant pulses from energetic pulsars.

The second class of model was noncataclysmic, so it could allow FRBs to repeat. Giant pulses are the very bright (\( \gtrsim 100 \) times the mean flux density) single pulses emitted by high-magnetic-field young pulsars, including the Crab Pulsar (53) and PSR J0540–6919 (54), which rotate at \(-20 \) to 30 Hz. Millisecond pulsars rotate at up to 700 Hz, and two examples that emit giant pulses are PSR B1937–21 (55) and PSR J1823–3021A, which is located in a globular cluster (56). FRBs are \( \gtrsim 1 \) billion times the luminosities of the most luminous giant pulses from the Crab Pulsar, although it has been suggested that FRBs could be a related phenomenon producing much rarer supergiant pulses (49) from highly energetic pulsars. The origin of the giant pulses is unclear, but if a pulsar’s propensity to emit a giant pulse depends upon its magnetic field and spin period, then there could be extremely magnetic and rapidly spinning neutron stars in the Universe (called millisecond magnetars) that could emit numerous FRB-like pulses, albeit for a very short time (less than a year) before they exhaust their rotational kinetic energy. If this model is correct, then FRBs would not be one-off sources and would preferentially be located in the spiral arms of star-forming galaxies (like young pulsars), possibly inside supernova remnants. They might also exhibit an underlying quasi-periodicity, like giant pulses, which tend to appear at particular rotation phases. Magnetars (neutron stars with high magnetic fields) would be expected in star-forming regions, but millisecond pulsars are known to occur both within globular clusters and the disks and halos of galaxies (57), because their rotational kinetic energy is sufficient to power them for more than the age of the Universe.

Some models did not fit into either category, such as those implying that FRB sources are within the Milky Way with spurious \( DM \), such as flare star models (58, 59). Although these models greatly reduced the required intrinsic luminosities, they required an alternative explanation for the dispersion of the pulses, necessitating a fine-tuned physical model to produce the observed dispersion sweep.

**Discovery of repeating FRBs**

Searches for repetition of the FRBs detected using Parkes found none after \( \gtrsim 100 \) hours of observation (44, 60). However in 2016, FRB 121102, then the only FRB detected using Arecibo, was found to repeat, producing many repeat bursts in a single observing session (61). It was nicknamed the repeater (later known as R1).

In follow-up observations of FRB 121102, 10 additional bursts were discovered, two on 1 day, then eight on another, with six appearing during a 10-min period. On other days, no bursts were seen (61). The repeater’s discovery ruled out the cataclysmic models, at least for for repeating FRBs. The bursts from FRB 121102 also appeared to come in clumps, unlike giant pulses from pulsars, which are more random (56, 62).

FRBs from the repeater appeared to be subtly different than the nonrepeating FRBs observed with Parkes and the GBT. Bursts from the repeater often had multiple components and were broader in temporal extent (\( \sim 5 \) versus \(-1 \) ms). These components were often confined to small fractional bandwidths (\( \delta v/v \sim 0.2 \)), with emission within each burst drifting to lower radio frequencies (Fig. 2B). This behavior had been predicted for radio emission from magnetars (63) before any FRB had been discovered. The emission has been described as being like a sad trombone, with multiple notes each progressively lower in tone (64).

The repeater’s active periods provided an opportunity for follow-up with interferometers to determine a precise location suitable for the identification of host galaxies. During one such active period, the realfast (65) instrument on the Very Large Array (VLA) interferometer detected an FRB (66) and localized it to near a persistent radio source and faint optical companion. Subsequent very long baseline interferometry further localized it to its host galaxy (67) and showed that it was situated coincident with the persistent radio source (68). The host was a tiny dwarf galaxy containing 40 million solar masses (\( M_\odot \)) in stars and gas, with a high specific star-formation rate of \( \sim 0.4 \, M_\odot \) year\(^{-1} \), with elemental abundances (metallicity) showing that it is still undergoing its first wave of star formation. The repeater’s host galaxy was very similar to those of many long-duration gamma-ray bursts and superluminous supernovae (69). Both of those types of transient are associated with young massive stars of low metallicity. The redshift (\( z = 0.193 \) (67), and hence distance, of the repeater’s host galaxy removed all remaining doubt that FRBs were at cosmological distances. FRB 121102 was at a distance of 972 Mpc, close to the maximum estimated for the Lorimer Burst (1).

The association with the persistent radio source raised several questions. Was the persistent source enabling the FRB emission, caused by the FRB, or merely coincident with it? Perhaps the persistent radio source was an accreting intermediate mass black hole or nearby supernova remnants powered by young neutron stars produced by recently exploded stars?

Follow-up observations of the repeater detected 93 further bursts (70, 71) between 4 and 8 GHz. These observations showed that, in its rest frame, FRB emission could extend to almost 10 GHz, but often with small fractional bandwidths. The repeater has a rotation measure of \( \sim 10^3 \) rad m\(^{-2} \), among the highest known for any astronomical source (72). This implied that it was in a highly magnetized environment, similar to the Galactic Center of the Milky Way, which contains a supermassive black hole.

Subsequent observations using broadband receivers (73) demonstrated that the repeater’s emission is often limited in frequency extent, with emission confined to the same finite radio bands for extended periods, which must be intrinsic to the source. Monitoring of the rotation measure has shown it varies over years, dropping to two-thirds of its original value, indicating a rapidly evolving magnetic environment (74).

Questions posed by the discovery of the repeater were: Do all FRBs repeat if observed for long enough? Are there two classes of FRB, repeaters and nonrepeaters? If every FRB source emits millions of FRBs (or more), then the formation rate of the sources could be very low, so the sources could potentially be highly exotic objects that are unknown from observations of the local Universe.

**2017–2022: The FRB age of discovery**

Most of the early FRBs were found with standard radio pulsar search instrumentation. Once the cosmological population was established, plans were made to accelerate the discovery rate using large field of view instruments. Some FRBs, such as the Lorimer Burst, were so bright that they should have been detectable by small dishes. Although small telescopes have much lower sensitivity, they also have wider fields of view than large dishes and are less expensive to build and operate. Purpose-built FRB facilities, both large and small, were constructed.

The UTMOST upgrade (Fig. 2C) of the large cylindrical Molonglo Observatory Synthesis Telescope (MOST) allowed an interferometer to identify FRBs in a blind survey (75). The Australian Square Kilometre Array Pathfinder (ASKAP) array (Fig. 2D) added an incoherent fast sampling mode to the 30-square-degree field of view (provided by its phased array feeds) and began detecting FRBs routinely, finding 20 in a fly’s eye survey (76). The phased array feeds removed the degeneracy between FRB flux and (usually unknown) position in the primary beam, enabling measurements of absolute flux densities for one-off FRBs. The nearby high-flux FRBs detected with ASKAP...
were shown to be local versions of fainter FRBs detected by the more sensitive Parkes dish in the more distant Universe (76). The expected $d \log N/d \log S = -3/2$ flux density distribution was beginning to be consistent with a cosmological population.

Many of these purpose-built facilities had the ability to buffer and store the raw data when an FRB occurred, which was determined automatically in real time. This enabled microsecond-time-resolution studies of FRB profiles, which revealed detailed microstructure down to only a few tens of microseconds (77, 78) (Figs. 2, C’ and D’). These short time scales indicate that the emission occurs on subkilometer scales, consistent with gaps in neutron star magnetospheres (79).

The Canadian Hydrogen Intensity Mapping Experiment (CHIME) telescope in Canada (Fig. 2E) has a very wide field of view (~200 square degrees) and high instantaneous sensitivity (collecting area of 8000 m²). This is complemented by the ASKAP interferometer’s sub-arc-second localizing capabilities and the even higher sensitivity provided by the 500-m Five-Hundred Meter Aperture Spherical Telescope (FAST) dish (Fig. 2F). A very different approach was taken by Survey for Transient Astronomical Radio Emission 2 (STARE2), which operates three 20-cm coaxial feeds (Fig. 2G), which have less than a millisecond of FAST’s collecting area but view the entire sky.

CHIME (80) is a fixed 4 × 100 m long × 20 m wide cylindrical interferometer that forms 1024 coherent beams over the sky. Its FRB sub-project CHIME/FRB searches for dispersed radio pulses almost continuously from 400 to 800 MHz, scanning the entire northern sky every day. The CHIME/FRB average detection rate (a few per day) has rapidly increased the catalog of known FRBs, which now has >600 unique sources. CHIME observations have provided insights into FRB emission at low (400 to 800 MHz) radio frequencies (81) and identified a large number of repeaters (82–84), many of which were localized with other facilities.

In early 2020, CHIME detected two FRB-like bursts of emission (85) from the Galactic magnetar SGR 1935+2154 separated by only 30 ms. Just a second earlier, STARE2 also detected a millisecond-duration radio burst (86) (Fig. 2G) at 1.4 GHz. The time delays between the two instruments were consistent with the delay caused by pulse dispersion. These radio bursts were coincident with an X-ray burst from the magnetar (87). Although the radio luminosity of the burst was 30 times weaker than the least luminous FRB then known, it demonstrated that magnetars could emit FRB-like emission. At least some FRBs, and possibly all, are emitted from magnetars.

The initial trillion-fold luminosity gap between the Lorimer Burst and Galactic pulsars has gradually closed, although a gap still persists (Fig. 3). The definition of what constitutes an FRB is also becoming blurred. Early observations of FRBs were often temporally smeared by the instrument and had approximately millisecond durations; however, as instrumentation improved, both intrinsically narrower and broader FRBs were observed. Periodic emission (88) has been reported in an unusually long ~3-s burst of radio emission, with periodic spikes at separations of 216.8 ms (Fig. 2F). Two other FRBs have potential periodic emission with periods of 2.8 and 10.7 ms (89). Do these reflect the rotation periods of neutron star hosts, or are FRBs similar to some radio magnetars that often exhibit spiky emission (89)?

Repeating FRBs

CHIME detected a second repeater, FRB 20180814A, which has a low DM of 189 pc cm⁻³, indicating a distance of only 350 Mpc (89). The detections increased so rapidly that there were soon another 17 repeaters (83, 84). In its first year of operation, CHIME detected a total of 18 repeaters (3.7%) and 474 FRBs that were not seen to repeat (96.3%) (90). The repeating FRBs have narrower fractional radio bandwidths and are wider than one-off FRBs (91). Follow-up interferometric observations (92) demonstrated that one of these repeaters (FRB 20180916B) was emitted from within a nearby spiral galaxy at a redshift of $z = 0.0337$ (170 Mpc). This FRB was six times closer than the original repeater (R1) and less luminous than previously observed extragalactic FRBs.

Analysis of the repeatet FRB 180916B showed the bursts were all received in a 5-day-wide window that recurred every 16.35 days, with more than half concentrated in a narrower 0.6-day-wide window (93). This motivated searches for periodicities in other repeaters. R1's bursts were then shown to be consistent with a 157 to 161 d periodicity with a broader fractional activity cycle (~50%) (94, 95). A consistent periodicity usually indicates either two stars in an orbit or precession, the reorientation of a spin axis (tracing out a conical shape). This led to the suggestion that repeating FRBs were magnetars orbiting other active (massive?) stars in such a way so that they are only observable at certain orbital phases (96). This model received some support when the radio frequency of bursts from repeating FRBs was shown to be (orbital?) phase dependent, with the lower-frequency FRBs coming later in the cycle than the high-frequency ones (97, 98).

Others (99) have suggested that repeating FRBs might be induced by material streaming past the wind and the magnetar wind produces cavities (cyan shading) separated by a shock front (cyan lines). The cavity preferentially emits high-frequency FRBs (blue and green wavy arrows) at the leading edge and lower-frequency FRBs (red wavy arrows) in the trailing sections. This model is an attempt to explain both the activity windows of some repeaters and their radio frequency time dependence.
A very high $DM = 1205$ pc cm$^{-3}$ repeating FRB observed with FAST was subsequently localized to a galaxy (105), which is much closer than the intergalactic DM model suggested, implying that the host galaxy must be contributing ~75% of the total dispersion. Like the original repeater, this FRB is associated with a persistent radio source that is probably related to the anomalous DM. This source demonstrates the potential pitfalls of assuming that the DM reliably predicts distances.

The linear polarization fraction of repeating FRBs was shown to be strongly radio frequency dependent, as predicted if their radio waves are scattered in a highly variable magnetic environment (106). At lower frequencies, radio waves experience more variable Faraday rotation, leading to the observed systematic depolarization.

**Host galaxies and cosmological applications**

Advances in instrumentation have enabled interferometers to determine the precise locations of one-off FRBs, identifying their host galaxies (107–109), as well as following up repeaters. A study of six repeating and 10 non-repeating FRBs with known host galaxies and redshifts (ranging from $z = 0.008$ to 0.66) found that there was no statistically significant difference between their host galaxies (110). However, the same study found that FRBs are rare in elliptical galaxies, being more common in galaxies that are experiencing at least some star formation (110). One-off FRBs are less common in galaxies with high star formation rates per unit mass, unlike long gamma-ray bursts, which are often associated with low-metallicity, low-mass hosts and produced by exploding massive stars. Nonrepeaters also appear to have different host galaxy properties to core-collapse supernovae (110). This is inconsistent with unification models proposing that all FRBs are from young magnetars produced in recent supernovae. Could nonrepeaters be produced by neutron stars reactivated long after their formation? One potential reactivation mechanism is mass transfer from a companion star. That process is known to produce millisecond pulsars, some of which emit giant pulses. Neutron stars in binaries accrete mass and gain angular momentum when their companions exhaust their fuel and swell up during stellar evolution. The length of the delay between neutron star birth and this accretion depends upon the mass of the companion star; it can be between 1 Myr and >1 Gyr. Millisecond pulsars could explain the host properties of one-off FRBs but not their lack of repetition.

Enough FRB host galaxies have been determined to derive an FRB redshift–DM relation (111) (also known as the Macquart relation). The observed relation is consistent with the total mass of baryons inferred by studies of the cosmic microwave background (112, 113), possibly resolving the difficulty in locating all of the baryons using other methods (29).

The sheer numbers of FRBs detected by CHIME are providing other insights into the population. Analysis of the catalog of detected FRBs (90) found that the $DM$ and flux density distributions are consistent with a cosmological population and with the large-scale structure of galaxies in the Universe (114).

FRB dispersion measures and host galaxy redshifts have been used to independently derive the value of the Hubble constant ($H_0$), the rate at which the expansion velocity of the Universe increases with distance. With a limited sample of nine FRBs with redshifts, a value of $H_0 = 62 \pm 9 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$ has been deduced (115), albeit with some possibly optimistic assumptions about the (contaminating) host galaxy $DM$ contributions. This is less precise than other methods; improvements will require eliminating FRBs with high local $DM$ contributions, possibly by examining their intrinsic widths and scattering or by characterizing their host galaxy environments.

**Current status and future prospects**

So what are FRBs? My personal view is that, like many new classes of object, FRBs will ultimately be shown to be composed of one or two dominant sources, but there could be other rarer classes of source with the right combination of magnetic field, rotation, gravity, and accelerated charged particles to generate FRBs. Determining the locations of ~100 FRBs should provide sufficient information on their host galaxies to constrain the progenitors. My leading contenders for the repeaters are magnetars, with some in orbit around massive stars, whereas nonrepeaters seem more likely to be rare giant pulses from high-magnetic field ($10^7$ G?) or recently spun-up millisecond pulsars. Both magnetars and millisecond pulsars experience magnetic field reconfigurations (Fig. 5) leading to changes in radio pulse shape changes. In magnetars, this can produce high-energy outbursts (116)—and in one case, a low-luminosity FRB (85, 86). Could these magnetic reconfigurations be a common trigger for FRB production? In millisecond pulsars, these reconfigurations are extremely rare, and of the few hundred known millisecond pulsars, only a few have been seen to exhibit them, including PSR J1713+0747 (117). If this model is correct, then eventually all FRBs might repeat, but we might have to wait decades or more to observe them.

I expect that progress in the field will be strongly linked to new facilities coming online in the next decade. The MeerTRAP (118) experiment is predicted to detect and localize FRBs at higher distances. The CRACO (Commensal Real-time ASKAP Fast Transients Coherent) upgrade to the ASKAP interferometer (set to become operational in late 2022) will coherently add the signals from the inner 30 antennas to improve the FRB localization rate by

![Fig. 5. Magnetar FRB emission model.](image-url)
an order of magnitude, whereas the Deep Synoptic Array (DSA 110) ([119]) (also coming in late 2022) is predicted to localize almost one FRB per day. The CHIME/FRB outrigger project is deploying additional cylinders to enable localization. The Canadian Hydrogen Observatory and Radio-transient Detector (CHORD) ([120]) will be an array of 512 6-m dishes supported by outrigger stations that will enable rapid localization of FRBs and should be operational some time in the mid 2020s. Farther in the future, instruments including the DSA 2000 ([121]) (circa 2027) plan to localize hundreds of FRBs per day and the Square Kilometre Array ([122]) (from 2030) is expected to probe high-redshift FRBs. The results from these new instruments will ensure that the golden age of FRB discovery extends well into the 2030s.

Would FRBs have ever been discovered if not for the brightness of the Lorimer Burst? Parallels have been drawn with the first gravitational wave source, which remains the one with the largest known amplitude (123, 124). The Lorimer Burst was only detected because it appeared in the sidelobes of the telescope, so in that sense, its high flux density was necessary for the discovery. However, the high fluence of the burst also compromised both its detection and its acceptance. The simple interference rejection algorithm in operation tried to erase the burst, and its brightness led to arguments that FRBs existed, but I am also certain that it was the scientific potential of FRBs that motivated the instrumental developments and surveys that ultimately produced the scientific discoveries discussed in this Review.

REFERENCES AND NOTES

1. D. R. Lorimer, M. Bailes, M. A. McLaughlin, D. J. Narkevic, F. Crawford, A bright millisecond radio burst of extragalactic origin. Science 318, 777–780 (2007). doi:10.1126/ science.1174532; pmid:1790298.

2. A. Hewish, S. J. Bell, J. D. H. Pilkington, P. F. Scott, R. A. Collins, Observation of a Rapidly Pulsating Radio Source. Nature 217, 709–713 (1968). doi:10.1038/217709a0.

3. B. W. Stappers, M. Kramer, Handbook of Pulsar Astronomy (Cambridge Univ. Press) (2012).

4. R. N. Manchester et al., The Parkes multi-beam pulsar survey - I. Observing and data analysis systems, discovery and timing of 100 pulsars. Mon. Not. R. Astron. Soc. 328, 37–35 (2001). doi:10.1046/j.1365-8711.2001.04731.x.

5. F. Crawford et al., Radio pulsars in the Magellanic clouds. Astrophys. J. 533, 367–374 (2001). doi:10.1086/320635.
