Fast radio bursts (FRBs) are millisecond bursts of radio radiation at frequencies of about 1 GHz, recently discovered in pulsar surveys. They have not yet been definitively identified with any other astronomical object or phenomenon. The bursts are strongly dispersed, indicating passage through a high column density of low density plasma. The most economical interpretation is that this is the intergalactic medium, indicating that FRB are at “cosmological” distances with redshifts in the range 0.3–1.3. Their inferred brightness temperatures are as high as $10^{37 \circ{\rm K}}$, implying coherent emission by “bunched” charges, as in radio pulsars. I review the astronomical sites, objects and emission processes that have been proposed as the origin of FRB, with particular attention to soft gamma repeaters (SGRs) and giant pulsar pulses.

Keywords: Fast radio bursts; pulsars; soft gamma repeaters; magnetars; intergalactic medium; nanoshots; giant pulses.

96.60.Gb; 97.60.Jd, 97.90.+j; 98.70.Dk

1. Introduction

Fast radio bursts (FRBs), initially reported in 2007\cite{ref1} were the first major unexpected astronomical discovery in decades. Although the astronomical community was skeptical, concerned that the single “Lorimer” burst initially reported might have been interference, the discovery of four additional bursts\cite{ref2} removed most doubt and led to a surge of research, both observational and theoretical.

Many FRB are so short ($\lesssim 1$ ms) that they are not temporally resolved by the receivers, and their nominal measured burst lengths must be considered only upper bounds on their intrinsic durations. They are therefore characterized by the time-integral of the flux $F_{\nu}$ received, called the fluence:

$$F_{\nu} \equiv \int F_{\nu}(t) \, dt,$$  \hspace{1cm} (1)
The most recent FRB Catalogue lists 17 bursts. Since then, one burst has been reported to repeat with 17 sub-bursts recorded over more than two years, eight of them clustered in a little over an hour and four in about 20 minutes (because of the exigencies of observing schedules, the absence of recorded bursts over a period of years does not imply that the source was inactive during that time). These sub-bursts extend in fluence down to the detection threshold, and it is plausible that more sensitive observations would detect many more.

Only one FRB has been associated with an astronomical object observed in any other manner, a galaxy at redshift $z = 0.492$ based on an apparent radio flare from that galaxy lasting several days following the FRB. The FRB itself was only located within a Parkes beam approximately 15′ across. The statistical significance of this association is controversial, and critics have suggested it is either an accidental coincidence with a variable active galactic nucleus or the effect of interstellar scintillation on a steady background source. The “afterglow” (the prolonged flare) had a fluence nearly $10^5$ times that of the FRB itself, which argues against, but does not disprove, the reality of an association.

Most known FRB were discovered by the High Time Resolution Universe project at the Parkes radio telescope in Australia. Their observed durations have been in the range 1–10 ms. The longer durations have been frequency-dependent, varying roughly $\propto \nu^{-4}$, consistent with multi-path broadening during their propagation. More sophisticated theories predict an exponent of $-4.4$, but observations of pulsars indicate exponents scattered over a broad range, mostly between $-3$ and $-4$. Most measured fluences are in the range $S = 1–10$ Jy-ms. The lower end of this range is approximately the limiting sensitivity for confident (signal to noise ratio $\geq 10$) detection at Parkes.

The energy of an FRB doesn’t arrive all at once. Instead, the higher frequency radiation arrives earlier, with a delay proportional to $\nu^\alpha$, where $\nu$ is the radiation frequency and $\alpha = -2$ to high accuracy. This dispersion is the result of propagation through dilute plasma, and its magnitude is proportional to the dispersion measure (DM), the integral along the propagation path (to high accuracy, a straight line of sight from source S to observer O) of the electron density $n_e$:

$$\text{DM} \equiv \int_S^O n_e \, d\ell.$$  \hfill (2)

Fitting DM to the raw measurement of flux vs. frequency is the first step in FRB signal processing, as it has been in pulsar astronomy since their discovery in 1967. Then, subtracting the frequency-dependent time delay, the fluxes across the spectrum are combined to give a frequency-integrated pulse profile.

Radio telescopes are orders of magnitude more sensitive than detectors of any other sort of radiation because of their large collecting areas (about 3000 m$^2$ for

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$a$1 Jy $\equiv 10^{-26}$ W/m$^2$ Hz = $10^{-23}$ erg/cm$^2$ s Hz.
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Parkes, 70,000 m$^2$ for Arecibo and nearly 200,000 m$^2$ for the Chinese FAST now under construction, although the effective areas of fixed dishes are significantly less than their nominal areas, and depend on the zenith angle) and because quantum noise is negligible at radio frequencies. Detection of weak radio sources is possible only because of this sensitivity, but it has the consequence that what is detected may be only an epiphenomenon representing a tiny fraction of a source’s total power. For example, the radio emission of a pulsar may be only $10^{-8}$ of its energy output. This deprives the theorist of the use of energy considerations as a tool for evaluating models.

2. Where Are They?

The first question an astronomer asks about a newly discovered object is its distance (its direction is usually known immediately from the instrument used to detect it). This is often a difficult question. Distances are usually impossible to determine directly because most astronomical objects are too distant for trigonometric parallax, particularly if they are observed only outside the visible band because the angular resolution of radio and X-ray telescopes is very crude (parallax measurements also require that the object remain detectable over months as the Earth moves around its orbit). Until the distance is determined, basic parameters such as luminosity and brightness are unknown, often to many orders of magnitude, and modeling is uncertain. For example, the distances of quasars and active galactic nuclei were controversial, even in order of magnitude, for several years after their discovery, and the distances of gamma-ray bursts for decades, and their theory was unguided until this uncertainty was removed.

The DM conveys valuable information about the location of a burst or pulsed source. Within our Galaxy, it gives an estimate of the path length of interstellar plasma through which the signal has propagated, and hence the source’s distance. FRB have values of DM too large to be explained in this manner, typically by a factor $\sim 10$, particularly because most FRB are observed in directions far from the slab-like Galactic disc, (at high “galactic latitude”, with the Galactic disc defining an equator). After subtraction of the (small) estimated Galactic component, the remaining DM must have another origin. An analogous argument shows that host galaxies, if they resemble our Galaxy, also cannot explain the dispersion measures, except in cases of fortuitous edge-on lines of sight.

There are two plausible sources of this extra-Galactic dispersion. One is the generic category of near-source plasma, whose nature depends on the astronomical object and environment that make the FRB. The other is the dilute (mean density $\approx 1.6 \times 10^{-7} (1 + z)^3$ cm$^{-3}$, where $z$ is the cosmic redshift) intergalactic plasma. No alternatives to these two have been found to be plausible.

A host galaxy resembling our Galaxy could not provide most of the dispersion measure unless it were fortuitously oriented almost exactly edge-on or the FRB were very close to a dense plasma cloud at its center. Clumping of intergalactic plasma
into clouds, such as the intra-cluster gas of clusters of galaxies, would not increase its mean density over its cosmologically determined value. Hence this could not produce mean DM greater than that of a mean intergalactic medium, and cannot provide an alternative to the inference of cosmological distances.

Determining whether the plasma dispersion is local to the source or results from passage through the intergalactic medium is necessary to understanding FRB because it determines their distances, astronomical environments, and energy scale. In this section I discuss the two possible hypotheses: near-source and intergalactic plasmas.

2.1. Near-source dispersion

If the dispersion is produced by plasma close to and associated with their sources, rather than by the intergalactic medium, then FRB may be our neighbors, on cosmic scales, possibly even within our Galaxy. At the high Galactic latitudes of most FRB, a Galactic origin would suggest distances of \( O(100) \) pc (1pc = 3.09 \( \times \) 10^{18} cm), the thickness of the Galactic disc. Greater (\( \gtrsim 100 \) kpc) distances \( D \) have been inferred from arguments based on the radiation emission of such plasma cloud\(^{17}\) and the spectral energy distribution of one FRB\(^{18}\). These distances would still be cosmologically local (\( z \ll 1; D \ll 3 \text{ Gpc} \)).

Any hypothetical dispersing cloud local to the source must satisfy a constraint on the electron density\(^{19,20}\)

\[
    n_e < \frac{2}{3} |−α − 2| \frac{m_e \omega^2}{4\pi e^2} \approx 5 \times 10^7 \text{ cm}^{-3}, \tag{3}
\]

where \( α ≈ −2 \) is the exponent in the dispersion delay \( δt \propto ν^α \) and \( ω \) is the (angular) frequency of the observed radiation; the tightest observational upper bound on \( |−α − 2| \) is 0.003, and other bounds are at most a few times larger; no inconsistency with \( α = −2 \) has been observed.

The observed DM of FRB are in the range 350–1600 pc cm\(^{-3}\), using astronomically convenient units, indicating dispersing clouds of dimension \( \gtrsim 3 \times 10^{13} \) cm, several hundred times the Solar radius. This bound is significant for models\(^{21,22}\) involving dispersion in stellar coronae or winds or other stellar phenomena. These values of DM are also far in excess of those of interstellar clouds, or of almost all paths in the Galactic interstellar medium, the exceptions being paths that pass very close to the Galactic nucleus\(^{19}\) or are almost exactly aligned with the Galactic plane (only one of the 17 known FRB). Similar constraints apply to dispersion attributed to interstellar matter in a host galaxy of a FRB.

A dispersing cloud must also be transparent to the observed radiation, which gives an analogous, but temperature-dependent, upper bound on \( n_e \):\(^{22}\)

\[
    n_e < 5 \times 10^3 \frac{T_{8000}^{3/2}}{DM_{1000}} \text{ cm}^{-3}, \tag{4}
\]

where \( T_{8000} \equiv T/8000^\circ\text{K} \) and \( DM_{1000} \equiv DM/1000 \) pc cm\(^{-3}\) (typical temperatures of dilute ionized interstellar matter, set by a balance between photoionization heating
and radiative cooling, are $\sim 8000 \, ^\circ K$). This bound appears to be much stricter than that of Eq. 3, but in regions of high energy density temperatures far in excess of $8000 \, ^\circ K$ are possible; in the Solar corona $T \sim 10^6 \, ^\circ K$.

If the dispersion is to be attributed to something other than the intergalactic medium, a origin associated with the FRB source itself must be found. One possibility is a region of dense plasma associated with a galactic nucleus, such as that known (from observations of pulsar dispersion) to exist within about 0.1 pc of the black hole (Sgr A*) at our Galactic center. It would then remain to be explained why FRB sources are invariably (every one of the 17 known) associated with such plasma clouds or galactic nuclei; the implied plasma electron density of $\mathcal{O}(10^4 \, cm^{-3})$ bears no obvious relation to any proposed FRB mechanism.

If FRB are found at the center of young supernova remnants (SNR), expanding massive shells of gas expelled in a visible supernova, most of the dispersion of the FRB may occur as it passes through the expanding plasma shell of the SNR. This hypothesis might explain the origin of the dispersion, associates it with the formation of a compact object capable of sudden energy release, like that of a FRB, and may be tested statistically. Fig. 1 shows the predicted cumulative distribution of FRB dispersion measures for high-Galactic latitude ($b > 20^\circ$) FRB, after subtraction of the estimated Galactic contributions (generally less than 10% of the measured values); low $b$ FRB are excluded because for them the Galactic contributions to DM are large and uncertain.

The dashed line is the predicted distribution with a fitted amplitude for a SNR shell of one Solar mass ($2 \times 10^{33} \, g$). The vertical lines show cutoffs if FRB sources turn off abruptly at the ages indicated, avoiding the divergence of numbers at low DM, for an assumed expansion velocity of 3000 km/s; FRB searches may also exclude low-DM events in order to discriminate against terrestrial interference. Despite these caveats, the shape of the distribution is clearly far from the prediction, evidence against SNR shells as the origin of FRB dispersion. No other model in which FRB are cosmologically local has yet offered a plausible explanation or testable predictions of the distribution of DM.

### 2.2. Intergalactic dispersion

If the dispersion of FRB is intergalactic, they are very distant, luminous and bright. Making standard cosmological assumptions, the distance to a FRB may be inferred from its DM. The results have been $z$ in the range 0.3–1.3, and distances between 1 and 4 Gpc. These “cosmological” distances imply, assuming isotropic emission, energies of $\sim 10^{38} - 10^{40} \, ergs$ for FRB.

This hypothesis predicts the distribution of DMs Fig. 2 compares the predicted cumulative distribution for FRB with $|b| > 20^\circ$ (because the Galactic contribution is large and uncertain at lower $|b|$ only high-$|b|$ FRB are considered) to that observed. The most important predicted feature is the rarity of FRB with small DM, a simple consequence of the Euclidean geometry of space in the local Universe.
This is confirmed by the data (although searches may exclude FRB with DM < 200 pc cm$^{-3}$ to avoid terrestrial interference). The absence of FRB with very large DM may be attributed either to their greater distances and redshifts (making them undetectably faint), to cosmic evolution of the event rate or to reduced sensitivity of their detection.

The hypothesis of cosmological distances makes an additional prediction. For low redshifts, space is nearly Euclidean, the inverse square law applies and the source function is close to its local value (because any cosmic evolution may be expanded as a Taylor series in $z$). Then the cumulative number of sources $N \propto S^{-3/2}$, where $S$ may be any quantity that follows an inverse square law. For steady or slowly varying radio sources, $S$ is the flux, and the failure of the $N \propto S^{-3/2}$ law demonstrated the existence of cosmic evolution (and hence of the Big Bang). For FRB, for which the peak flux cannot be deconvolved from the effects of multipath propagation and instrumental response, we take $S$ to be the burst fluence. The results are shown in Fig. 3.

They are consistent with the hypothesis of a uniformly filled Euclidean space, except for the (previously noted) anomalously bright “Lorimer” burst. Perhaps this is accounted for by observational selection: it is natural to impose extraordinarily conservative criteria before accepting the reality of a new phenomenon. A
speculative alternative is a spatially limited local enhancement of the burst rate. The deficiency of bursts with $S < 1$ Jy ms is likely attributable to the detection threshold.

We also plot the fluence $S$ against DM in Fig. 4. If the sources were standard candles in a Euclidean universe they would lie on a curved line $S \propto DM^{-2}$. Two curves of this form are shown. Although Euclidean geometry is a good approximation at these DMs, assuming the intergalactic medium is the source of the dispersion, there is no indication that the sources are standard candles. The apparent deficiency of detections in the lower right corner of the plot may be attributed to the difficulty of detecting highly dispersed weak bursts.

An additional and independent argument in favor of “cosmological” distances of FRB is the recent discovery of linear polarization and measurement of Faraday rotation, parametrized by the rotation measure $RM$, in FRB 110523. Combining this with the DM gives the electron density-weighted mean parallel component of magnetic field along the propagation path

$$\langle B_\parallel \rangle_{n_e} = \frac{RM}{DM} \equiv \frac{\int n_e B_\parallel d\ell}{\int n_e d\ell} = 0.37 \mu G.$$  (5)
Fig. 3. Distribution of cumulative number of observed FRB vs. fluence, and a fitted $N \propto S^{-3/2}$ line, showing good agreement. No Galactic latitude cut is made because the interstellar medium does not affect fluence measurements. To maintain a homogeneous sample, only the 15 FRB detected at Parkes are included; the single (repeating) burst discovered at Arecibo and the single burst discovered by the Green Bank Telescope are excluded. However, the location of the observed FRB within the Parkes beams is not known (with the possible exception of the Lorimer burst, detected in three beams, from whose signal ratios a location may be inferred), so all fluence values are given as if the sources were at the centers of the detecting beams, and are in fact lower bounds. For sources randomly distributed on the sky this does not affect the predicted exponent in the limit of large $N$. Data from the FRB Catalogue except for FRB 130628.

This is an order of magnitude less than typical interstellar magnetic fields in our Galaxy and several orders of magnitude less than plausible fields in denser plasma clouds. It indicates that nearly all the dispersion occurs in regions of very low (sub-$\mu$G) fields. The only such regions known are the intergalactic plasma and the gas within clusters of galaxies, but the latter do not have sufficient dispersion measure to account for the observed values.

2.3. Pulse Broadening

Several FRB have pulse widths $W$ greater than the resolution (after de-dispersion) of the measurements, which is about 1 ms. The steep frequency dependence of $W$ (approximately $\propto \nu^{-4}$) indicates that these widths result from multi-path propagation delays. Plotting $W$ against DM (Fig. 5) shows no correlation between these variables. This implies that scattering in the intergalactic medium cannot be the cause of the broadening, in agreement with theoretical arguments.

In several FRB $W$ is much greater than plausible for Galactic propagation paths.
Fig. 4. Distribution of FRB in S-DM space. There is no evidence that FRB are standard candles, and the apparent deficiency of weak highly dispersed bursts may be a result of observational selection. Data from.

at their high Galactic latitude, and hence must attributed to near-source regions. However, the measured \( W \) are not atypical of those of Galactic pulsars with similar DM\(^{13} \) after scaling to the frequencies at which FRB are observed, suggesting that comparable regions may be found in our Galaxy. These highly scattering regions may be dense star-forming clouds; it has been suggested\(^{16} \) that they may be the environs of galactic nuclei.

3. What Are They?

The fact that a FRB has been observed to repeat\(^{4, 5} \) rules out models that involve the destruction or irreversible transformation of the source. These include proposals of stellar collapse, merging binaries and catastrophic collisions.

FRB are plausibly produced by compact young remnants of stellar collapse, neutron stars or black holes, whose deep gravitational potential wells permit the sudden emission of energy. This hypothesis has been incarnated as soft gamma repeaters (SGRs)\(^{16–18, 25, 31–34} \) or giant pulses from young pulsars\(^{25, 35–38} \); these are all rare, episodic but repeating events of low duty factor. Related ideas have included the interaction of pulsars with planets\(^{39} \), asteroids or comets\(^{40, 41} \). Less exotic models, applicable only if FRB are not at cosmological distances, have appealed to events like stellar flares\(^{21, 22} \).
The observed short durations of FRB imply small emitting regions, because emission over larger regions would, by a spread in radiation travel times $\Delta t$, produce longer pulses; in the absence of relativistic bulk (including phase) motion $\Delta t \geq \Delta r/c$, where $\Delta t$ is the observed burst duration and $\Delta r$ is the dimension of the radiating region (properly, its dimension along the direction of radiation).

The observed $\Delta t \lesssim 1 \text{ ms}$ (before broadening by multipath propagation) implies small source regions, and a correspondingly high radiation intensity at the source. This is usually described by a “brightness temperature” $T_b$:

$$T_b \equiv \frac{F_{\nu}c^2}{2\nu^2k_B},$$

the temperature (in the Wein limit, applicable at radio frequencies) of a black body emitting the flux density of radiation $F_{\nu}$, whose units are ergs/s cm$^2$ Hz sterad. Because the angular sizes of compact sources are not directly measured, it is usually assumed that their emitting areas $A \sim (c\Delta t)^2$ and that $F_{\nu} \sim F_{\nu,\text{obs}}(4\pi D^2/A)$, where $F_{\nu,\text{obs}}$ is the observed spectral density integrated over the (unknown) source solid angle, and has units ergs/s cm$^2$ Hz, tacitly assuming isotropic emission. By Liouville’s theorem, the brightness temperature of the radiation we observe is the same as that at the source; we just observe it in the tiny (not directly observed, but calculated from the inferred source size and distance) solid angle subtended by the source, while at the source it is assumed to fill steradians.
FRB have $T_b$ up to $\sim 10^{37} \degree K$. Of course, these extraordinary values do not indicate any emitter with that physical temperature, or even particles with the corresponding energy $k_B T_b$. Just as for pulsars, extraordinary $T_b$ indicate coherent radiation by “bunches” or coherent waves containing large numbers of particles. In fact, the “nanoshots” of at least one pulsar had $T_b$ higher even than those of FRB. Theoretical plasma physics has so far been incapable to explaining the high brightness of radio pulsars (without which they would be unobservably faint), and this is likely to be the most difficult aspect of FRB to understand.

The short durations of FRB (the upper limit on the light travel times across their sources ($c \Delta t < 3 \times 10^7$ cm) exclude a source region larger than a neutron star (radius $R = 10^6$ cm) or stellar mass black hole (Schwarzschild radius $3 \times 10^5(M/M_\odot)$ cm, where $M_\odot$ is the Solar mass). They permit small emitting subregions of larger objects, such as stellar flares. The only other astronomical phenomena with time scales as short as those of FRB are the rise times of the giant flares of Soft Gamma Repeaters, which have been observed to be 200–300 $\mu$s and pulses, sub-pulses and “nanoshots” of radio pulsars some of which have durations $\leq 0.4$ ns.

All of these are produced by neutron stars. Neutron stars are also regions of high gravitational, and in some cases high magnetic, energy density, and hence natural origins of energetic events. Two classes of sudden neutron star outbursts have been considered candidates for the origin of FRB:

### 3.1. Soft Gamma Repeaters

SGR were suggested as candidate FRB sources shortly after their discovery, and have been advocated many times since. SGR and FRB have several similarities: characteristic time scales, low duty factors and repetition. They also have an important difference: SGR appear to be entirely thermal phenomena, radiating black body-like spectra of X- and gamma-rays. Heterogeneous temperatures mean that the integrated spectra need not be Planckian, but they are heavily self-absorbed at low frequencies, with brightness temperatures close to the material temperature; SGR outbursts are not observed at frequencies below the X-ray range. This is entirely unlike FRB, which are observed only in radio waves, with extraordinarily high brightness temperatures.

Attempts to explain FRB as a consequence of SGR sources (N.B.: they might not be associated with SGR outbursts themselves, even if produced by the same strongly magnetized neutron stars) have had to appeal to models of “magnetar” (hyper-magnetic) neutron star magnetospheres with $B \sim 10^{14} - 10^{15}$ G. The model assumes that a substantial part of the neutron star’s magnetic moment, inferred from its spin-down rate by treating it as a rotating dipole in vacuum, has its source in currents flowing through the near-vacuum magnetosphere rather than the dense neutron star interior. In magnetar models of SGR these currents may be induced by fracture and motion in the neutron star’s solid crust, but in the FRB model they were frozen-in during the collapse that formed the neutron star. The
currents cannot be rapidly interrupted because the large circuit inductance would produce an electromotive force that would spark across the gap; instead, they decay slowly, over hundreds to thousands of years, consistent with the ages of the neutron stars identified as SGR sources.

The ultimate energy source for both the SGR and FRB activity is the magnetostatic energy of the neutron star. Although a magnetic field may be characterized by a magnetic energy density $B^2/8\pi$, this energy is global rather than local and cannot be carved out like a scoop of ice cream. Even though the magnetostatic energy density may be high in vacuum, it cannot be released there because there is no charge on which an induced electric field can do work. If energy is released below the neutron star’s surface, it diffuses to the surface as thermal X-rays over an extended period of time, explaining neither the rapid rise of a SGR outburst nor a FRB. Hence it must be released in the current-carrying magnetosphere, and SGR and FRB activity stops when the magnetospheric currents decay.

To explain FRB it is necessary to assume that when the right conditions are met the impedance along the magnetospheric current path suddenly increases, leading to rapid dissipation of energy. This is the classic mechanism of magnetic reconnection. In this model it may be produced by single-particle Coulomb scattering because electrostatic quasi-neutrality requires that the magnetospheric ion density be proportional to the current density. If, as a result of flow in the neutron star itself that changes the frozen-in magnetic field, the magnetospheric current density increases, the electron density must also increase (because the current-carrying electrons are relativistic), and quasi-neutrality requires an equal increase in the ion density. But electron-ion scattering limits the mean electron velocity to $c$ divided by the number of scatterings along a magnetospheric path. This imposes a maximum current density because the mean electron velocity is inversely proportional to the ion density, and hence to the electron density. This is in contrast to an ordinary plasma in which the mean electron velocity can increase to carry an increasing inductively-driven current density.

The result is likely to be a sudden increase in electromotive force and energy deposition as the current fails to keep up with its inductive drive. Then, by a *deus ex machina*, plasma instability leads to intense coherent emission. This plausibly occurs during the rapid rise of a SGR giant flare, occurring on a sub-ms time scale is consistent with that of FRB (even though the full width of a SGR flare, emitting a thermal spectrum, is typically hundreds of ms), before the released energy has thermalized. This hypothesis is difficult to evaluate or test, an unsatisfactory state of affairs, also true of pulsar emission mechanisms.

Unfortunately, this model of FRB as counterparts of SGR may fail because the Parkes telescope did not detect a FRB when it was fortuitously observing during an outburst of SGR 1806-20. The telescope was pointing away from the SGR, but even its far side-lobe sensitivity is $\sim 10^{-6}$ of its main-lobe sensitivity, while a FRB at the distance of the SGR (about 9 kpc) would be expected to be about $10^{11}$ times as bright as one at typical “cosmological” distances of $\sim 3$ Gpc. The SGR model
of FRB predicts\cite{20,11} that any radio telescope searching (with high time resolution and de-dispersing signals) for transients or pulsars would detect an extraordinarily strong FRB signal, equivalent to $\sim 10^5$ Jy ms ($10^4$–$10^5$ times the fluence of observed FRB) in-beam, during a Galactic SGR outburst that is above its horizon. The FRB would show the dispersion of the Galactic interstellar medium between it and the observer; the DM of SGR 1806-20 is not known because it is not observed at radio frequencies, but it might be expected, based on its distance in the Galactic plane, to be $\sim 300$ pc cm$^{-3}$.

There may be loopholes in this argument that the failure to detect a FRB simultaneous with SGR 1806-20 excludes the SGR origin of FRB\cite{34}. Perhaps the relation between observable FRB and SGR is not 1:1. For example, the extremely nonthermal FRB emission may be strongly beamed. Alternatively, a FRB may have been broadened in propagating through the interstellar medium by an amount outside the 14–56 ms broadening window used in the observations at the time of SGR 1806-20\cite{51}.

### 3.2. Giant pulsar pulses and nanoshots

Some radio pulsars emit, in addition to their regular pulses with durations of ms (or tens or hundreds of $\mu$s for “millisecond” pulsars with periods of 1–10 ms) very intense and much shorter bursts called “nanoshots”\cite{43,45}. Although these are not energetic enough to be detected at distances of hundreds of kpc or greater, they are empirical evidence (not theoretically understood) of pulsar behavior. Can analogous behavior on much higher energy scales produce FRB even at cosmological distances?

#### 3.2.1. Nanoshots

It is first necessary to consider the physics of nanoshots and its possible extrapolation to higher energies. Two very different pulsars have been observed to produce nanoshots. One was the Crab pulsar, with a spin period of 33.5 ms and (polar, in a dipole model) magnetic field $B_p = 4 \times 10^{12}$ G. The other was PSR B1937+21, a millisecond pulsar with a spin period of 1.558 ms and (polar, in a dipole model) magnetic field $B_p = 4 \times 10^8$ G. PSR B1937+21 is believed to be a “recycled” old pulsar, whose magnetic field decayed and spin slowed, but that was subsequently spun-up by accretion from a (now lost) close binary companion. In contrast, the Crab pulsar is the product of a supernova in the year 1054. Taking the distance to the Crab pulsar $D = 2.2$ kpc and $D \geq 3.6$ kpc to PSR B1937+21, and assuming isotropic emission, their nanoshot energies and durations were

$$E = 4\pi D^2 F_\nu \Delta \nu = \begin{cases} 1.0 \times 10^{28} \text{ ergs} & \Delta t \leq 0.4 \text{ ns} \quad \text{Crab} \\ 1.2 \times 10^{27} \text{ ergs} & \Delta t \leq 15 \text{ ns} \quad \text{B1937+21} \\ 1 \times 10^{40} \text{ ergs} & \Delta t \leq 1 \text{ ms} \quad \text{FRB} \end{cases} \quad (7)$$
where the fluence integrated over the bandwidth $\Delta \nu$ was measured and corresponding numbers for FRB are included.

If the source regions were not moving relativistically, their volumes may be estimated as $\sim (c \Delta t)^3$. Supposing it were possible to annihilate magnetostatic energy in the source region and to radiate it as the radio-frequency energy of a nanoshot with unit efficiency, the lower bound on the nominal corresponding magnetic field:

$$B_{\text{nom}} = \sqrt{\frac{8\pi E}{(c \Delta t)^3}} \geq \begin{cases} 1.2 \times 10^{15} \text{ G} & \text{Crab} \\ 1.8 \times 10^{10} \text{ G} & \text{B1937+21} \\ 5 \times 10^{11} \text{ G} & \text{FRB}, \end{cases} \quad (8)$$

where for the FRB $c \Delta t$ is replaced by a neutron star radius $R = 10^6$ cm. For the two pulsars, the implied magnetic fields and energy densities appear to exceed those at the surfaces of the neutron stars by large factors, a problem that was pointed out by the discoverers of nanoshots indicating the failure of a naive model based on magnetostatic energy. It is conceivable that the local fields are much larger than the dipole fields, as in sunspots; for the fast-rotating PSR B1937+21 this hypothesis predicts a large, and perhaps measurable, braking index if high magnetic multipole moments dominate the spindown.

Even if $B_{\text{nom}}$ were less than $B_p$, it would not explain the origin of the nanoshot energy. A vacuum magnetic field, whose source is currents within the star, cannot dissipate energy. But the pulsars known to emit nanoshots are rapidly rotating, suggesting that rotation is essential (in contrast to SGR/magnetars whose physics is believed to be that of a non-rotating magnetosphere). The spindown torque is exerted on the star through currents flowing on its open field lines. They intersect the stellar surface on a pole cap of area $\pi R^2 \Omega/c$, where $\Omega$ the angular frequency of rotation. The spindown power density on the polar cap is

$$I = \frac{1}{6} \left[ \frac{(B_p R^3)^2 \Omega^4}{c^3} \right] \frac{c}{\pi R^3 \Omega} = \frac{B_p^2 c}{6\pi} \left( \frac{\Omega R}{c} \right)^3. \quad (9)$$

Some unknown portion of this may be available to power nanoshots.

If the plasma source of the nanoshots is moving towards the observer with a bulk Lorentz factor $\Gamma$, then only a solid angle $\sim \Gamma^2$ sterad is illuminated, rather than $4\pi$ sterad, with a corresponding reduction in the total energy required. The duty factor of observed nanoshots is very small, so this may be consistent with their observation in a significant fraction, perhaps all (unsuccessful searches do not appear to have been published), of the pulsars examined at high time resolution.

Bulk relativistic motion also implies that the radius of the emitting region that is observed over an interval $\Delta t$ is $\sim c\Delta t \Gamma$, with area $\sim (c\Delta t \Gamma)^2$, and its depth along the line of sight is $\sim c\Delta t \Gamma^2$. The volume that can contribute to the nanoshot is $\sim (c\Delta t \Gamma)^3$, implying a total energy

$$E_{\text{max}} \sim \frac{B_p^2 c}{6\pi} \left( \frac{\Omega R}{c} \right)^3 (c \Delta t \Gamma^2) \Delta t \Gamma^4 \sim \begin{cases} 4 \times 10^{20} \Gamma^4 \text{ ergs} & \text{Crab} \\ 2 \times 10^{21} \Gamma^4 \text{ ergs} & \text{B1937+21}. \end{cases} \quad (10)$$
These values should be compared to the inferred nanoshot energies, allowing for beaming,

\[ E \sim \begin{cases} 
1 \times 10^{27} \Gamma^{-2} \text{ ergs} & \text{Crab} \\
1 \times 10^{26} \Gamma^{-2} \text{ ergs} & \text{B1937+21}
\end{cases} \tag{11} \]

The maximum theoretical energies are consistent with observations if \( \Gamma \gtrsim 10 \). Of course, this does not explain how the spindown power makes the observed nanoshots; it only shows that it is consistent with the energetic constraints.

3.2.2. FRB?

These arguments can be modified to apply to giant pulse models of FRB. Only bounds on FRB intrinsic durations are known, and these bounds are \( \sim 10^6 \) times longer than the measured nanoshot durations. The condition that the FRB energy not exceed the product of spindown power and its intrinsic duration

\[ E < \frac{1}{6} \left( \frac{B_p R^3}{c^3} \right) \Omega^4 \Delta t = 6 \times 10^{46} B_{15}^2 \Omega_4^4 \Delta t_{-3} \text{ ergs}, \tag{12} \]

where \( B_{15} \equiv B_p/10^{15} \text{ G}, \Omega_4 \equiv \Omega/10^4 \text{ s}^{-1} \) and \( \Delta t_{-3} \equiv \Delta t/10^{-3} \text{ s} \); the dimensionless parameters have been normalized to their maximum credible values. Equivalently, the source parameters are constrained

\[ B_{15}^2 \Omega_4^4 \Delta t_{-3} > 1.6 \times 10^{-7} E_{40}, \tag{13} \]

where \( E_{40} \equiv E/10^{40} \text{ ergs} \). There is ample room in parameter space to satisfy this inequality, even allowing for inefficiency in converting rotational energy to radiation.

The bounds of Eqs. 12 and 13 use the actual pulse energy \( E \), that may be less, perhaps by a large factor, than that inferred from the measured fluence by assuming isotropic emission.

The observation of repetitions of FRB 121102 over nearly three years\cite{4,5} sets a lower bound on the spin-down time

\[ t_{\text{spin-down}} = 3 \frac{I c^3}{B^2_p R^6 \Omega^2} \approx \frac{10^3}{B_{15}^2 \Omega_4^2} \text{ s} \geq 10^8 \text{ s}, \tag{14} \]

where \( I \approx 10^{45} \text{ g cm}^2 \) is the neutron star moment of inertia, or

\[ B_{15}^2 \Omega_4^2 \Delta t_{-3} > 10^{-5}. \tag{15} \]

Combining with Eq. 13 yields

\[ \Omega_4^2 \Delta t_{-3} > 1.6 \times 10^{-2} E_{40}. \tag{16} \]

Because \( \Omega_4 \) cannot much exceed unity, this sets a non-trivial lower bound on \( \Delta t \) of about \( 10^{-5} \text{ s} \) in the model of FRB as giant pulsar pulses at cosmological distances. This bound is relaxed if the observed emission is beamed towards us.

The observation that \( \Delta t_{-3} \leq 1 \) sets a lower bound on the spin frequency

\[ \Omega_4 > 0.13 E_{40}^{1/2}; \tag{17} \]
the spin period of the most energetic (observed, and assuming isotropic emission) FRB cannot exceed 5 ms. Then Eq. 15 implies

$$B_{15} < \frac{1}{300 \Omega_4} < \frac{1}{40} \sqrt{\frac{\Delta t - \frac{3}{3}}{E_{40}}}.$$  \hfill (18)

Combining Eqs. 13 and 14 bounds the spin-down time

$$t_{\text{spin-down}} < 200 \frac{\Delta t - \frac{3}{3}}{E_{40}} \Omega_4^2 \text{ y.}$$  \hfill (19)

Again, this bound is relaxed if the burst is beamed.

If FRB are produced by such rapidly slowing neutron stars then they must be quite young, and perhaps the product of supernovae in the era of photographic, or even CCD, astronomy. The contribution of the remnant, if fully ionized and not clumped (contrary to expectation\textsuperscript{54}), to the dispersion measure would be

$$DM_{\text{SNR}} = \frac{M_{\text{SNR}}}{M_\odot} \frac{30 \text{ pc cm}^{-3}}{(A_d v_{30,000})^2},$$

where \(A_d\) is the SNR’s age in decades, \(M\) its mass, \(v_{30,000} \equiv v/30,000\text{ km/s}\) and \(v\) is its expansion velocity. The absence of any significant change in the dispersion measure of the repeating FRB 121102\textsuperscript{4, 5} over nearly three years thus sets a lower bound, if the remnant is spherically symmetric and ionized (for example, by collision with surrounding gas or by internal shocks) \(A_d v_{30,000} > 3\) in this model.

The preceding numerical estimates combine the shortest \(\Delta t\), the greatest \(E\) and the span of repetitions of the sole FRB that has been observed to repeat as if they described the same object, and assume isotropic emission if \(E\) is obtained from the observed fluence. In fact, they were observed for different FRB, so that the numerical inferences tacitly assume that all FRB have similar characteristics, as well as Occam’s assumption of the simplest possible interpretation.

The hypothesis that FRB are giant pulsar pulses at cosmological distances requires them to be in a fairly narrow corner of parameter space, but it is not excluded. It leads to a number of qualitative predictions, or at least suggestions:

1. FRB are preceded by supernovae, probably by years to a century.
2. FRB dispersion measures will decrease to an asymptotic (intergalactic medium) value if the supernova remnant makes a measurable contribution.
3. Repetitions of FRB will continue over their spin-down times of years to a century.
4. The repeated bursts will gradually decrease in energy as the neutron star slows and its spindown power decreases.
5. Even at cosmological distances, FRB may be observable as millisecond pulsars, perhaps either at radio or visible frequencies, with spindown times of years to a century (longer if beamed).
3.2.3. Propagation

Quite apart from their demonstration of intense emission, the observations of nanoshots showed that nanosecond pulses can travel through the plasma of the Galactic plane for substantial distances (about 2.2 kpc for the Crab pulsar and $\geq 3.6$ kpc for PSR B1937+21) without significant broadening by multipath propagation. The nanoshots are less broadened than would be expected on the basis of the broadening of pulsar pulses measured with poorer temporal resolution at these distances and dispersion measures.\textsuperscript{13, 14}

Perhaps there are, in fact, multiple propagation paths, with significant time delays between them, so that in observations with nanosecond temporal resolution the different paths produce distinct, apparently unrelated, spikes rather than a smoothly broadened pulse. In geometrical optics a focus forms at an extremum of the optical path (travel time), so that a single image will not be broadened if diffractive effects are negligible. That hypothesis would imply even more energetic nanoshots because the detected energy would be only a fraction of the total.

4. Discussion

The development of multi-dish radio telescopes, planned to culminate in the square kilometer array with collecting area of $10^6$ m$^2$,\textsuperscript{55} more than an order of magnitude greater than that of Arecibo and five times that of FAST, will lead to the observation of much larger numbers of fainter FRB. The faint (some as weak as 0.1 Jy ms) repetitions of FRB 121102 were observed at Arecibo and the Green Bank Telescope, with collecting areas 22 and 2.4 times that of Parkes, respectively. The actual detection rate will depend on how the telescope is used (many simultaneous beams with moderate sensitivity or a single beam collecting energy from its entire aperture), on unknown properties of the FRB population: their intrinsic “luminosity function” (event rate as a function of radiated energy, more properly called a fluence function because it is the fluence rather than the flux that is measured), and their spectra and distribution in the Universe because redshift affects the detectability of cosmologically distant events.

Positive identification of a FRB with some other astronomical object would greatly advance our understanding. The recognition of trains of repetitive outbursts of a single FRB is a giant step in this direction because it will permit the use of interferometry to determine an accurate position on the sky (observations at a single telescope can only determine position to approximately its beam width, about 15'$ at Parkes).

Identification would likely immediately resolve the question of the distance scale to FRB, because at least approximate estimates of the distances to most other classes of astronomical objects are known, and measurement of their redshift gives an immediate and accurate distance measurement of cosmologically distant objects. The critical step to understanding of gamma-ray bursts, after more than two decades of perplexity, was their identification on the basis of temporal coincidence
with visible light transients whose coordinates were determined to arc-seconds by visible imaging. Then identification with galaxies with measurable redshifts was immediate, and provided conclusive proof that they are at cosmological distances. The suggested FRB association with a distant galaxy would be equally conclusive, if it is confirmed, either by statistical arguments or by another identification. Identification might also give clues as to the FRB mechanism if they are associated with some sort of peculiar object.

The fluences of FRB have complex non-monotonic frequency dependence. The several bursts of the repeating FRB 121102 show that this changes from burst to burst. Studies of the frequency structure of the single burst FRB 110523 indicate that this structure may be attributable to scintillation produced by refraction along the propagation path. This is consistent with the rapid (on time scales of minutes) changes in spectrum of the repeating FRB. From this rapidly growing body of data, and comparison with the scintillation of Galactic pulsars, it will be possible to extract information about the plasma environments of FRB.

The reader will note the large number of references from 2016 in this review that was completed March 31, 2016. This subject is developing rapidly. We may hope that an understanding of the astronomical nature and environments of FRB will soon be developed, even if the mechanism of their coherent emission remains as enigmatic as that of pulsars, which they may resemble.

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