What are Fast Radio Bursts?

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Physical constraints on the sources of Fast Radio Bursts are few, and therefore viable theoretical models are many. However, no one model can match all the available observational characteristics, meaning that these radio bursts remain one of astrophysics’ most mysterious phenomena.

1 Introduction

Fast Radio Bursts (FRBs) are a relatively new astrophysical mystery. Their novelty means that the field is rapidly changing, and some aspects of this article may become outdated in the month from submission to publication.

A large number of models for FRB progenitors have been proposed, many more than can be readily summarized in this Comment. I present the current collection of physical constraints, as well as some basic caveats, and compare a representative sample of models against these. Many models only aim to explain a subset of evidence (for example, cataclysmic models will not repeat, and therefore will fail to explain FRB 121102, the only known repeating FRB), but given the early days of the field, I allow consideration of the possibility that more than one mechanism is at play. I summarize with a forward look, pointing to upcoming promising lines of evidence.
FRBs are defined as radio-frequency impulses more highly dispersed than allowed by the Milky Way's diffuse ionized medium\textsuperscript{12,28}, and this dispersion is quantified in the dispersion measure (DM), measured in parsecs per cubic centimetre. The excess DM (over that imposed by the Milky Way) is presumably due to the immediate vicinity of the FRB, or propagation through the intergalactic medium (IGM). The IGM contribution cannot be larger than the observed DM, placing an upper bound on their distance \(D\), and thus a lower bound on their spatial number density. Their radial position could be anything from terrestrial to cosmological\textsuperscript{10}. The inferred space density is high if a large fraction of the DM is physically associated with FRBs, which I call the local scenario: \(D \sim 10\text{-}2,000\) Mpc. In these scenarios, the DM could be dominated by dense plasmas, including supernova remnants, \ion{H}{II} regions, circumnuclear gas, or stellar outflows/atmospheres. Placing FRBs much closer would result in their event rate being dominated by the nearest neighbouring galaxies, while more distant distributions are likely affected by cosmological evolution. The nearby scenarios share Euclidean statistics\textsuperscript{25}: as one increases the sensitivity by a factor of 4, one probes to twice the distance, or eight times the volume, and expects eight times the event rate (analogous to Olber's paradox), and sources are described by a flux count slope \(d\ln N/d\ln S\) of -1.5, where \(N\) denotes the number of bursts of flux \(S\). This slope should be uncorrelated with any other properties, e.g. DM. If a correlation between DM and flux is found, it would rule out all local models.

The majority of information (and bursts) come from a single object, FRB121102, for which the distance, host galaxy, and repetition statistics are known. Its repetition is non-Poissonian\textsuperscript{20}, and it is certainly possible that all FRBs function by the same mechanism (see the Comment by
Manisha Caleb et al. in this issue). While some FRBs have been followed up extensively without detection of repetition, there also appear to be extended periods of months where FRB121102 does not repeat.

Extrapolating from a single event to a population results in large uncertainties. FRB121102 is consistent with both local and cosmological scenarios. Being the only event detected by Arecibo Observatory, which searched a small area of sky very deeply, in a local scenario it could easily be the furthest of all bursts.

2 Constraints on FRB sources

Energetics. the total energy of FRBs is modest: the typical energy of 1 Jy-ms at 1 GHz for a distance of 1 Gpc is $10^{30}$ J, comparable to the Crab Pulsar spin-down energy, and smaller than soft gamma-ray outbursts. All FRB models are built to explain the basic energetics. The harder challenge is the emission in gigahertz radio waves: most mechanisms propose an energy injection with an unknown conversion process, with the notable exception of primordial dipoles.

Coherence. A separate challenging aspect of FRB mechanisms is the high observed brightness temperature. If the physical size of the source is no larger than the apparent duration of the event, this corresponds to a range of a few to thousands of kilometres. Converting the radiation field to an equivalent brightness temperature yields $10^{40+}$ K, higher than the Planck Temperature!

The same challenge exists for short duration giant pulses, or nanoshots, observed in pul-
Presumably the emission region is not thermal, but rather consists of coherent motions of electrons: the brightness temperature of an FM radio station is $10^{32}$K, also comparable to the Planck temperature. This is a statement that all the electrons are moving coherently, and not in a thermally random fashion. This precludes synchrotron emission. The coherent conversion poses a physical challenge to any mechanism, somewhat analogous to the gamma-ray burst non-thermal constraint. Very few models propose a quantitative physical mechanism to achieve this.

**Additional constraints.** FRBs all appear to scintillate, similar to pulsars. Almost no other radio sources are compact enough ($\lesssim$ nano-arcseconds) enough to scintillate on megahertz frequency scales from plasma lenses in the Milky Way. FRBs exhibit frequency structures that are not power laws. This could be due to plasma lensing near the source\(^4\),\(^ {16}\), or intrinsic to the source. The latter is challenging to understand: the energy densities involved require relativistic degrees of freedom, which tends to result in a spread of frequencies due to the relativistic Doppler shifts. The superradiance proposal (see below) is an exception, which generically predicts frequency structure. Any characteristic resonant length scale would need to be small, on the order of a metre, which does not have any known physical candidate mechanism. An analogous mystery is the gigahertz banding structure in Crab interpulses (for recent summary, see\(^5\)).

**Magnetic properties:** Some FRBs are highly polarized, led by FRBs 110523 and 150215\(^23\). For many events, polarization information was not recorded, and the high RM ($\sim 10^5$) observed in the Repeater would have been bandwidth smeared, so it is possible that all FRBs are highly polarized. The RM varies from small to very large, and the larger values are imprinted near the
source. The only other line of sight known to lead to a comparably high RM is the Galactic Centre, with magnetar J1745-2900 showing an RM \( \sim 10^5 \) as well. Both it and FRB121102 show non-monotonic RM variations on timescales of a month.

The above properties are ideally explained by model(s) of FRBs. Most models only attempt to address a subset of the known constraints, but many are at odds with the collective data. This would be expected if more than one mechanism of generating FRBs exists.

3 Models of FRB progenitors

I list a selection of models in decreasing order of mundaneness:

**Radio frequency interference (RFI):** terrestrial signals had initially been a concern, and some events (perytons) were indeed traced back to a microwave oven. VLBI detection ruled out interference for the Repeater, as it is unthinkable for the voltages to correlate across continents. Perytons serve as a concrete example of an identified signal that shares similarities with FRBs, demonstrating the possibility of multiple populations.

**Flare Stars:** some stars are known to exhibit short time variation radio emission in radio flares, making them a potential FRB candidate. These stars might be in the Galactic halo, with the DM imprinted in the stellar corona. Models predict some deviation from the \( \lambda^2 \) dispersion law, and cannot explain the few bursts where the wavelength dependence has been precisely measured.
**Neutron star/pulsar subcategories:** Young pulsar giant pulses: Maxim Lyutikov discussed the energetics\(^1\), which can be met in a local scenario. Magnetars have substantial energy stored in magnetic fields, which might be released. The repeating burst shows a number of similarities with the Galactic Centre magnetar\(^{17,21}\). Objects may hit pulsars\(^3\), they can quake\(^{31}\) and transition between phases\(^{26}\). The compact nature of neutron stars and the **known unknown** mechanism of their radio emission makes them popular, though mostly non-predictive.

Blitzars: the collapse of a neutron star into a black hole is called a Blitzar\(^7\). Magnetic fields have to release their energy since black holes can’t have hair, and may accelerate electrons to produce the radio bursts.

**Black hole accretion flows:** it is not surprising that the energetics near black holes has been invoked to power FRBs\(^{30}\). The short duration can be associated with a wandering beam, analogous to shining a laser pointer into space.

**Superradiance:** a version of maser emission, this postulates a radio line in a relativistic disk orbiting a black hole to smear into the broad observed radio features\(^9\). This and the following model are one of the very few which describe a quantifiable coherent emission mechanism.

**Dark matter:** some models of magnetic dipole dark matter\(^{27}\) predict many of the subsequently observed properties, including irregular repetition, a flat spectral index and a high RM.

**Black hole explosions:** In the generic Hawking picture, primordial black holes emit their
final gasp when they reach the radius (or inverse temperature) of massive particles, e.g. electrons. One would expect highly energetic gamma-rays to emit. Some proposals increase this radius using virtual white holes\(^1\) to explode with \(\sim\)centimetre sizes, thus leading to FRBs.

**Cosmic strings**: it has been proposed that cosmic string loop cusps can result in radio emission\(^2\). While these do not quantitatively explain the coherent spectrum of FRBs, they do predict non-association with galaxies, which is rather unique.

**Intelligent alien signals**: not sure how such proposals got through the refereeing process\(^13\), which surely have the fewest robust predictions!

Combination of models can be, and have been, created using combinations of these mechanisms, for example black holes and neutron stars. Many more models have been proposed, which this short Comment is unable to do justice to. We summarize the models in Table 1.
| Location                  | Model                        | repetition | Faraday rotation | $\frac{d\ln N_{\text{enr}}}{d\ln S}$ | Implications                          | DM range (pc cm$^{-3}$) | Scattering |
|---------------------------|------------------------------|------------|------------------|--------------------------------------|-------------------------------|------------------------|------------|
| Cosmological (≳ $2h^{-1}$Gpc) | blitzars                    | ×          | 10               | ?                                     | gravitational waves            | $10^{3-4}$            | ×          |
|                           | merging compact objects     | ×          | 10               | ?                                     | type Ia SNe, X-ray, γ-ray      | $10^{3-4}$            | ×          |
|                           | magnetar flare              | ✓          | 10               | ?                                     | ∼ms TeV burst                  | $10^{3-4}$            | ✓          |
|                           | dipole dark matter          | ✓          | $10^{3-5}$       | ?                                     | flat radio spectrum            | $10^{3-4}$            | ✓          |
|                           | cosmic strings              | ×          | 10               | ?                                     | no galaxy association          | $10^{3-4}$            | ×          |
|                           | superradiance               | ✓          | $10^{3-6}$       | ?                                     | spectral regularity            | 300-2500              | ✓          |
|                           | edge-on disk                | ✓          | Resolvable scattering |                                      |                                | 10-2000               | ✓          |
| Extragalactic, local (≲ $2h^{-1}$Gpc) | primordial BHs             | ×          | 10               | -3/2                                  | distributed like dark matter  | 300-2500              | ×          |
|                           | nuclear                     | ✓          | $10^{3-5}$       | -3/2                                  | near black hole                | 10-3000               | ✓          |
|                           | magnetar                    |             |                   |                                       |                                |                       |            |
|                           | SNR pulsar                  | ✓          | $10^{1-3}$       | -3/2                                  | archival SNe or SNR            | $10^{2-10^{4}}$       | ✓          |
|                           | flaring MS stars            | ✓          | $\text{RM}_{\text{gal}} > -3/2$ |                                      | main sequence star             | ≥ 300                 | ×          |
|                           | RFI                         | ✓          | 1                 | ?                                     | diurnal variation              | ?                     | ×          |

Table 1: This table summarizes a number of FRB models by classifying them as cosmological, extragalactic but local, Galactic, and terrestrial. The seven columns are potential observables of FRBs and each row gives their consequence for a given model (Blitzars: 7), compact object mergers 18,29, bursts from magnetars 14, dipole dark matter 27, cosmic strings 2, superradiance 9, edge-on disk galaxies 32, exploding primordial blackholes 1, circumnuclear magnetars 21, supernova remnant pulsars, stellar flares 11, and terrestrial RFI 8.). The parameters are generic expectations of models, and lying outside this range does not necessarily rule them out. Even though all models have to explain the observed 180-2,600 pc cm$^{-3}$, some models predict a wider range of DM. For instance, in the circumnuclear magnetar or edge-on disk disk scenarios there ought to be bursts at relatively low DM that simply have not been identified as FRBs.
4 Conclusions

The FRB phenomenon has stimulated broad ideas to generate the short-time energetic coherent radio emission observed. All FRB’s share the coherence phenomenon. The repeating FRB121102 presents many challenges, hinting to activity near a black hole inferred from the high RM – no other locale is known to have such a high RM. Magnetic dipoles, and neutron stars are viable candidates. The dipole dark matter model is the only one which makes predictions on properties, including polarization angle, spectral index, etc. Resorting to known unknowns is required in pulsar interpretations, since the pulsar radio emission mechanism itself is still not understood.

More than one category of sources may be responsible: in the history of gamma-ray bursts (see the Comment by S. R. Kulkarni in this issue), some repeated, while most do not. Similarly, FRB show a wide variety of properties, and thus might not all be the same.

Some models may permit ready counterpart tests if localized through very long baseline interferometry within their host galaxy: nuclear, supernovae (remnants). Localization of the burst to its nearest galaxy will discriminate between broad distance classes, though it is unlikely to pinpoint any specific model.

Independent of their physical nature, the coherence of FRBs is assumed to provide us with a rich new probe of our universe: as we spend billions building synchrotron light sources on earth, FRB are much more coherent and powerful, enabling true interferometry through their lensed multipath propagation. The burst path lengths of $10^{25}\text{m}$ are probed to $10^{-3}\text{m}$, corresponding to a
dimensionless strain of $10^{-28}$, potentially the most precise measurement available. It could probe space-time, from lensing\textsuperscript{19} to gravitational waves\textsuperscript{24} to deviations from gravity\textsuperscript{33}.

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