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Review

Solving the Mystery of Fast Radio Bursts: A Detective's Approach

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Abstract: Fast radio bursts (FRBs) are still a mystery in contemporary astrophysics. Unlike many other astronomical objects whose basic physical mechanism is already identified and the research on which focuses mainly on refining details, FRBs are still largely unknown regarding their source(s) and radiation mechanism(s). To make progress in the field, a "top-down" or "detective's approach" is desirable. I will summarize how some key observational facts have narrowed down the options to interpret FRBs and show that at least some FRBs are produced from the magnetospheres of highly magnetized neutron stars (or magnetars). I will also argue that the current data seem to favor a type of coherent inverse Compton scattering process by relativistic particle bunches off a low-frequency wave propagating in the magnetosphere. This brief contribution is a shorter version of an extended review to be published in *Reviews of Modern Physics*, and it was written as a tribute to the 80th anniversary of Remo Ruffini.

Keywords: fast radio bursts; magnetars; coherent radio emission

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1. Prologue

The 80th birthday of Prof. Remo Ruffini was on 17 May 2022. Because of the COVID-19 pandemic, I was not able to attend the dedicated celebration conference in person but was invited to deliver a remote talk. Incidentally, I had the pleasure of celebrating his 77th birthday three years earlier at the 2019 Nanjing GRB conference. I have known Remo for many years, meeting with him at numerous conferences in high-energy astrophysics. Our research overlaps in the field of gamma-ray bursts (GRBs). Even though we often interpret GRB phenomenology differently, I have enjoyed many conversations with him about the physics of GRBs and other subjects.

Our different views on GRBs stem from the different approaches we have taken to tackle the GRB problem. As a distinguished relativistist, Remo often adopts a doctrinal or "bottom-up" approach by setting up a theoretical framework to begin with and matching observations with the theories. The examples include his theory of electromagnetic black holes and the fireshell model for GRBs (e.g., [1–3]) to interpret GRB prompt emission and afterglow, and his progenitor models involving a list of binary systems (e.g., [4]). The approach I and many others take is the opposite. We start with the observational data and ask ourselves what the data really tell us. By ruling out various possibilities (including some of our own ideas that were proposed before the relevant data became available), we finally narrowed down the most probable interpretations of the phenomenon. Such a "top-down" approach is analogous to the approach of a detective who tries to unveil a crime scene. My understanding of the GRB phenomenology has been summarized in the book titled "The Physics of Gamma-Ray Bursts" [5].

In research fields such as GRBs and fast radio bursts (FRBs), whose data are quite sparse in the early stage of development, I believe that the detective's approach is more fruitful. Our initial bets usually turn out incorrect, and new surprising discoveries keep flooding in, forcing continuous revisions of the theoretical framework.

The talk I remotely presented at Ruffini's 80th birthday meeting was titled "The Physics of Fast Radio Bursts". The content of the talk has been explained in detail in my long review article in press at the *Reviews of Modern Physics* [6]. This short contribution is a highlight of that review, with a focus on how the detective's approach bears fruit in this rapidly developing field.

2. The Source(s) of FRBs

FRBs [7,8] were first reported in 2007 as highly dispersed, millisecond-duration bursts detected in the radio band (from ∼110 MHz to ∼8 GHz), see also an earlier controversial case [9]. According to [10] and the FRB theory catalog (https://frbtheorycat.org/index.php/Main_Page, accessed on 13 June 2019), there are more than 50 models proposed in the literature. Most of these models have been critically commented on in [6], with most of them already disfavored by the data. In the following, I will list the key observations that have greatly narrowed down the possible source models to interpret FRBs.

The key observational clues that are related to the source(s) of FRBs include the following:

- The smoking gun: An MJy radio burst (FRB 200428) was observed from the Galactic magnetar SGR J1935+2154, which was temporally associated with a moderately bright X-ray burst [11–16]. The radio burst, if observed from nearby galaxies, would appear as a low-luminosity FRB. This suggests that at least magnetars can make FRBs, and at least some FRBs are made by magnetars. The majority of X-ray bursts emitted from this source were, however, NOT associated with FRBs [17], suggesting that special conditions are needed for a magnetar to make FRB-like events. Later, a radio pulsar phase was observed from the magnetar. The pulses are found to be confined in a narrow phase window. FRB bursts, on the other hand, appear in random rotation phases, suggesting that the bursts and pulses likely originate from different locations and probably have somewhat different mechanisms (albeit sharing similar physics) [18].
- Cosmological FRBs are observed to have two apparent types: repeaters and non-repeaters. There have been intense discussions regarding whether all FRBs repeat (e.g., [19–22]). Some observations show that repeating bursts have some special features (e.g., broader pulses and narrower spectra [23]). However, as the observing time increases, some previously named non-repeaters turn into repeaters [24]. The separation between the two populations becomes more blurred.
- There are several very active repeaters that, when monitored closely with the Five-hundred-meter Aperture Spherical radio Telescope (FAST) in China, have a burst rate exceeding 100 per hour [25–29].
- Two active repeaters, FRB 20121102A [30] and FRB 20190520B [31], are located inside a persistent radio source (PRS). Other repeaters, on the other hand, do not have detectable PRSs. The two PRS repeaters also have large Faraday rotation measure (RM) values, suggesting a possible dense and highly magnetized environment. The RM values of some active repeaters also undergo significant long-term [32] and short-term [26] variations, sometimes with significant sign reversals [33,34]. All these are, however, not necessary conditions to produce an active repeater. FRB 20220912A has a negligibly small and non-varying RM yet actively emits many bursts with the total burst energy budget comparable to other active repeaters [29].
- The host galaxies of FRBs (both repeaters and apparent non-repeaters) seem to be mostly Milky-Way-like massive galaxies, unlike the star-forming dwarf host galaxies of long GRBs and superluminous supernovae [35–42]. The positions of FRBs within the host galaxies also typically have large offsets from the star-forming regions [26,38,39]. The global properties are more analogous to Type II supernovae, Type Ia supernovae, and even short GRBs [43]. The DM distribution of the FRBs from the CHIME first catalog seems to require a delayed channel from star formation, at least for some FRBs [44–46], even though the star formation model is consistent with the data if some nearby (low DM) samples are removed [47].
- The existence of FRBs with a delayed channel is solidified by the discovery of FRB 20200120E in a globular cluster of a nearby spiral galaxy M81 at a distance of

3.6 Mpc [48,49]. The bursts from the source have lower luminosities than typical cosmological FRBs, suggesting that there could be many more such sources from far away galaxies that have evaded detection [50–52].

- Most repeaters do not have a detectable apparent periodicity. There are two special cases detected by the CHIME/FRB collaboration: (1) FRB 20180916B has an apparent $\sim$16 day periodicity [53] with frequency-dependent active phases [54,55]. Close monitoring of other active repeaters with the FAST telescope does not show significant periodic signals (the tentative $\sim$157-day period for FRB 20121102A [56] does not increase significance with time P. Wang et al. 2023, in prep). (2) FRB 20191221A, was identified to show a 216.8(1) ms periodicity with a significance of 6.5σ [57], but since it has a roughly 3 s-long duration which is much longer than the typical millisecond duration of other FRBs, this FRB is likely a special case and may have a different origin from the majority of FRBs.

So what do these clues tell us about the FRB sources? Here is a list of statements one may make after performing a detective's analysis:

- Magnetars can make FRBs;
- At least some FRBs are produced by moderate-age magnetars such as SGR J1935+2154. Because the source of FRB 200428 (SGR J1935+2154) continues to emit more X-ray bursts later, the magnetar FRB sources must be FRB repeaters;
- Since we have not detected an active FRB repeater in the Milky Way galaxy, the active repeaters at cosmological distances may require a different interpretation. Additionally, since none of the Galactic magnetars are known to be located in globular clusters, the source of FRB 20200120E must be somewhat different from the source of FRB 200428.
- For the above reasons, overall, there may exist at least three types or sub-types of repeating FRB sources: SGR J1935+2154-like magnetars, active repeater sources, and globular cluster sources.
- If magnetars are the common engine for all repeating FRBs, then there might be at least three sub-categories of magnetars: the common ones such as SGR J1935+2154 that make FRB 200428-like bursts with a low repetition rate, the special magnetars (presumably younger) that power active repeaters (with the caveat that some of these active repeaters are also located in regions offset from the main galaxy light), and more special magnetars newly born in globular clusters.
- An alternative, more speculative but exciting possibility is that at least some cosmological FRBs do not originate from self-bursting magnetars. Interacting neutron stars or even black hole systems are other well-motivated possibilities and cannot be easily ruled out with the current data.
- The immediate environment of active repeaters can be either highly magnetized and dynamically evolving or the opposite. In some cases, the environment is consistent with a dense magnetized nebula or a magnetized companion in a binary system, but in some other cases, there is no evidence of any of such a complicated environment. This suggests that the emission sources of FRBs should not rely heavily on the environment to produce the bursts.
- There are no definite clues yet that some apparent non-repeaters must originate from catastrophic events. A possible case of intrinsic one-off FRB from a plausible association between an FRB and a gravitational wave event has been suggested [58], but the case is controversial: Ref. [59] suggested that the association is physically impossible if the host galaxy is the one suggested in [60]. More observations are needed to see whether another distinct class of FRBs can be established.

3. The Radiation Mechanism(s) of FRBs

Because of their high fluxes, short durations, and large distances, FRBs have the most extreme high brightness temperatures in the universe, reaching $T_b \sim 10^{36}$ K and higher. This raises great challenges in identifying their coherent radiation mechanism(s). In [6], I have reviewed in depth various FRB radiation models proposed in the literature and discussed the pros and cons of these models in confrontation with the data. Here I just summarize the main observations and the constraints posed by them.

The key observational clues that are related to the radiation mechanism(s) of FRBs include the following:

- The typical duration of FRBs is milliseconds, but some FRBs have rapid variability as short as 60 nanoseconds [50].
- Most observed FRBs are highly polarized. Most have nearly 100% linear polarization [32,61–63]. A small fraction of bursts from a growing population of sources have measurable circular polarization, some even up to 70% [26,64–68].
- Most bursts with high linear polarization degrees have polarization angle (PA) nearly constant during the bursts [32,69], but cases with significant PA variations have been observed in bursts from some sources [61,62,69].
- The isotropic burst energy emitted in the radio band during the timescale of an active episode of repeater sources (ranging from a few days to 1–2 months) is of the order of a few $\sim 10^{43}$ erg [25–29].
- Some FRBs, especially non-repeaters, show wide spectra with emissions covering the entire bandpass of the telescopes. For repeaters, on the other hand, the spectra are typically narrow [23]. Case studies of many bursts from FRB 20201124A [27], and FRB 20220912A [29] suggest that some bursts even have $\delta\nu/\nu_0$ as small as <0.3.
- Some bursts, especially those of repeaters, show an interesting frequency down-drifting feature (also called the "sad-trombone" effect), with higher frequency emission arriving earlier and lower frequency emission arriving later [23,27,70].

FRB emission models within the magnetar framework may be generally grouped into two categories. The first category borrows insight from modeling radio pulsars and invokes pulsar magnetospheres (either inside the magnetosphere or slightly outside the magnetosphere in the current sheet region beyond the light cylinder), which may be called "closer-in" or "pulsar-like" models. The second category invokes highly magnetized relativistic shocks far from the engine. The physical processes in such a scenario share some aspects with GRBs. Such models may be termed "farther-out" or "GRB-like" models. These models have been discussed in great detail in [6] with many original papers cited. In the following section, I summarize some key constraints on these models based on the observational facts listed above.

- Polarization angle (PA) swing is a key observational feature of radio pulsars. As the line of sight sweeps across different field lines when the neutron star rotates, different PAs are observed. The characteristic signature is an "S" shape or its inverse, which is consistent with the dipolar geometry of magnetic fields conjectured for pulsars. The variation becomes smaller if the line of sight tangentially cuts the emission cone or the emission height is large. Conversely, the synchrotron maser model invoking a magnetized relativistic shock demands parallel magnetic field lines to achieve coherence and, therefore, only predicts non-varying PAs across a burst. Such non-varying PAs are indeed observed in most bursts [32,69], but the detection of varying PAs [61,63] from both repeating and non-repeating FRBs rules out the shock model at least for some FRBs. Since the magnetospheric models can account for both varying and non-varying PAs, diverse PA variations offer strong support to the magnetospheric origin of FRBs.
- Circular polarization [26,68,69] can be produced either from intrinsic radiation mechanisms or propagation effects [71]. The detection of significant circular polarization from a large fraction of bursts from the clean-environment active repeater FRB 20220912A [29] suggests that circular polarization is very likely unrelated to the propagation effect in the external medium. Since synchrotron maser emission cannot produce bright bursts with significant circular polarization [71] whereas magnetospheric models can do so [71–73] via coherent curvature [74,75] or inverse Compton scattering [76] or through propagation effects within the magnetosphere [71], the

circular polarization data therefore also disfavor the GRB-like models and favor the pulsar-like models.
- The 60-ns variability timescale [50] poses a significant challenge to the GRB-like shock model [51]. The duration of the burst w defines an FRB emission radius $R_{\rm FRB} \sim cw\Gamma^2$. A variability timescale $\delta t \ll w$ would have to be attributed to small patches in a relativistic jet, which introduces a very low efficiency for emission [77]. This argument was well known in the GRB field to argue against the external shock model for GRB prompt emission.
- The narrow spectrum $\delta\nu/\nu_0 < 0.3$ observed in some repeaters [27,29] poses a generic constraint on the GRB-like model, and even challenges most of the pulsar-like models ([78], Y. Qu, P. Kumar and B. Zhang, 2023, in preparation).
- The relativistic shock model predicts a small radio emission efficiency of the order of 10^{-4} [79]. Pulsar-like models are more flexible since the pulsar radio emission efficiency can range from 10^{-7} to $\sim$1 [80]. The Galactic FRB 200428 has an efficiency of the order of 10^{-4}, which can be accounted for in both models. However, if extragalactic FRBs have the similar efficiency, even if there is a global beaming factor $f_B \sim 0.1$, the observed $\sim$$10^{43}$ erg isotropic radio burst emission energy measured during active episodes for a few repeaters would suggest a total energy of a few times 10^{46} erg within an active episode, which is already a significant fraction of the dipolar magnetic energy of a magnetar [25–29]. This suggests that if extragalactic FRBs are powered by magnetars, the GRB-like models already suffer from the energetics problem. The pulsar-like models are still allowed if they can make FRBs much more efficiently than the 10^{-4} efficiency.
- The sad-trombone effect can be naturally interpreted within the pulsar-like model using the "radius-to-frequency-mapping" effect widely discussed in pulsar models [81,82]. This effect can also be accounted for within the shock model, even though some special conditions are required [83,84].

In summary, many independent pieces of evidence point toward a consistent picture in favor of a magnetospheric origin of at least some, and probably most, FRBs if magnetars are the common source engine of FRBs.

4. Magnetospheric Coherent Inverse Compton Scattering as an Attractive Mechanism to Power FRB Emission

Within the magnetospheric models, based on the observational clues collected so far, I personally favor a mechanism invoking the upscattering of a certain type of low-frequency waves by relativistic particle bunches within the magnetosphere of a magnetar. The simplest scenario is to invoke a low-frequency electromagnetic wave, which might be excited by oscillations of near-surface charges induced by crust cracking [76]. The advantages of this model in interpreting the observations include the following:

- It provides an alternative to the traditional model invoking coherent curvature radiation by bunches. It inherits the merit of that model that invokes the magnetar magnetosphere as the emission site but can overcome some difficulties encountered by the curvature radiation model.
- One difficulty of the coherent curvature radiation model is the plasma suppression effect. Because of the huge brightness temperatures of FRBs, the required bunches need to have a very large plasma density (or a high multiplicity with respect to the Goldreich–Julian density), which exacerbates the plasma suppression effect that has been discussed within the context of pulsar emission [85]. The emission power of the inverse Compton scattering (ICS) process for individual particles is a few orders of magnitude larger than that of curvature radiation, which suggests that a dense plasma is not needed for such a mechanism to power bright FRB emission [76]. The plasma suppression effect is no longer relevant. Even for the curvature radiation model, the plasma suppression effect may become irrelevant when one considers a parallel electric field in the emission region, which will separate the opposite charges

in the plasma [86]. Such an $E_{\parallel}$ is needed in FRB models invoking coherent radiation by bunches (for both curvature radiation and ICS) in order to overcome efficient cooling of the bunches to maintain a large enough power to produce an FRB [74,76] and mandate a low-twist magnetar model [87].

- Another major difficulty for coherent curvature radiation by bunches is how to produce and maintain bunches with the right size that corresponds to the observed wavelength. Two stream instabilities have been widely invoked to generate bunches, but the characteristic frequencies for those instabilities involve the plasma frequency, which is not obvious how it is related to the observed FRB frequency. The ICS process provides a way to naturally bunch the particles. In the rest-frame of a relativistically moving particle, the electric field of the incident wave (which is Dopper boosted from the low-frequency wave) provides an oscillating force that naturally bunches the particles in the scale of the wavelength in the comoving frame. The emitted electromagnetic wave (due to Thomson scattering in the comoving frame) carries the same frequency, which is Doppler boosted in the observer frame to the FRB frequency. As a result, the emitting particles are naturally bunched within the wavelength of the emitted waves. This provides a very natural bunching mechanism not shared by the curvature radiation mechanism.
- The maintenance of the bunches within the FRB models (both for curvature radiation and ICS) is attributed to the $E_{\parallel}$ in the emission region, which is demanded by the energetics argument [74,76]. Such an $E_{\parallel}$ allows the bunches to emit in the radiation-reaction-limited regime. In such a regime, the particle energy distribution would maintain a narrow distribution due to the "thermostat" effect, i.e., the particles with a larger energy than the critical Lorentz factor defined by the radiation-reaction-limit condition would undergo stronger radiative cooling to lose energy, whereas the particles with lower energy than the critical Lorentz factor would undergo further acceleration via $E_{\parallel}$. As a result, the particle distribution within the bunch would maintain a value around the critical Lorentz factor so that the bunch is not easily dispersed.
- Curvature radiation is intrinsically a wide-band spectrum characterized by the modified Bessel's function for a single electron. The ICS process, on the other hand, could produce a much narrower spectrum for a single electron, given that the low-frequency wave itself has a narrow spectrum (which is possible since its frequency may correspond to a characteristic mode of neutron star crustal oscillations). As a result, the ICS process has a better prospect of producing narrow spectra, as observed than the curvature radiation model.

5. Epilogue

The history of GRB studies has shown the power of the top-down approach. With the combination of observational data and theoretical modeling, a standard physical framework has been established for GRBs, with the final major piece of the GRB paradigm collected in 2017 (the gravitational wave - short GRB association) 50 years after the discovery of the first GRB. The field of FRB research shares a similar history as the GRB field but with an expedited pace. At the time of writing, we are still in the process of putting together a coherent physical picture for FRBs. The bullet points summarized in the previous sections are my best guess as a detective at the stage of writing. It is almost certain that some of these statements will turn out incorrect when more observations bring further clues. This contribution, in any case, serves as an intermediate record that may be reviewed and entertained later.

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