Physical Mechanisms of FRBs: Clues from Data and Progress in Theory

Bing Zhang (UNLV)

ABSTRACT

I will discuss three main questions regarding the physical mechanisms of FRBs using observational data, especially those collected from the FAST telescope, some of which are first reported. The topics include "What?", "Where?", and "How?". I will show predominant evidence of the magnetospheric origin of FRBs, discuss the production and propagation of FRBs, and comment on the pros and cons of the magnetar model and the possibility of other source types.

The main questions to understand the physical mechanisms of FRBs include: 1. What is (are) the source(s) of FRBs? The FRB 200428 detection suggests that magnetars can make FRBs, but can they do it all? 2. Within the magnetar scenario, where is the emission region of FRBs? Is it inside / slightly outside the magnetosphere (pulsar-like) or from relativistic shocks far from the central engine (GRB-like)? 3. How are FRBs with extremely high brightness temperatures made through one (or more) coherent radiation mechanism(s)? Answering these questions requires both observational data and theoretical insights and modeling. I will discuss these three questions in turn (with the "What?" question discussed in the end).

• **Where?** I will show the following predominant clues suggesting that FRBs originate from a region in the outer part (or slightly outside) the magnetosphere of a rotating central engine (a magnetar or something similar): 1. The two sub-bursts of FRB 200428 roughly coincide with the two X-ray peaks of the associated X-ray burst from SGR J1935+2154, and we know magnetar X-ray bursts are of a magnetospheric origin. 2. Even though the polarization angle (PA) within a single burst is consistent with being constant in some cases (which can be also explained in the magnetosphere models), cases of swinging PA with time within a burst have been observed in some bursts (both repeating or non-repeating), which demands a magnetospheric origin (Luo et al. 2022). 3. Thousands of bursts have been detected from a few active repeating FRBs (Li et al. 2021; Xu et al. 2022), sometimes with a burst rate > 500 per hour (Zhang et al. 2022). Clusters of FRBs (e.g. a cluster of 11 bursts within 0.2 s) have been discovered (Zhou et al. 2022). The short waiting time may be challenging for the synchrotron maser model but is not a problem for emission from a rotating magnetosphere. 4. The total burst energy emitted in month-timescale, when assuming a radio efficiency of $\eta \sim 10^{-5}$ and global beaming factor $f_b \sim 0.1$, already reaches several times 10^{46} erg, a significant fraction of the total magnetic energy of a magnetar (Li et al. 2021; Zhang et al. 2022). This requires more efficient radio emission and narrower beaming, which would be consistent with the magnetospheric origin. Alternatively, the source may not be a magnetar. There was a theoretical criticism that bright FRBs may not be able to escape a magnetar magnetosphere (Beloborodov 2021). However, a detailed study shows that bright FRBs can escape the magnetosphere under realistic FRB magnetosphere emission conditions that invoke a relativistic particle flow in the open field line region (Qu, Kumar, & Zhang 2022).

• **How?** A widely discussed magnetosphere FRB model is coherent curvature radiation by bunches. I discuss a new model that invokes coherent inverse Compton scattering by bunches (Zhang 2022). The hypothesis is that the crustal oscillation that drives Alfvén waves will also drive near-surface charge oscillations which will emit low-frequency electromagnetic waves. These waves can freely propagate through the magnetosphere and inverse-Compton scattered by relativistic particles in the charge starved region. The ICS emission power of a single electron is (7-8) orders of magnitude higher than that of curvature radiation.

The required degree of coherence is significantly reduced compared with curvature radiation. Radiation is highly linearly polarized. The emission has a narrow spectrum, consistent with observations.

• **What?** The active repeaters may or may not be magnetars. At least they reside in a dynamically evolving, highly magnetized environment, signified by rapid RM variation or even reversal (Xu et al. 2022; Anna-Thomaset al. 2022), possibly with a massive star or black hole companion. FRB host galaxies and redshift distribution are not consistent with tracking active star formation. Some older population sources are needed. Finally, a potential GW190425-FRB 20190425A association (Moroianuet al. 2022) is consistent with the production of a non-repeating FRB during the collapse of supramassive NS following a BNS merger (Zhang 2014) through the blitzar mechanism (Falcke & Rezzolla 2014).

Self-introduction:

Bing Zhang is a professor in the Department of Physics and Astronomy, the University of Nevada, Las Vegas (UNLV), and the Director of the Nevada Center for Astrophysics. He is a theorist actively collaborating with observers. He received his PhD degree in 1997 from Peking University, China. His PhD thesis and the work during the first two postdocs (Peking University/Australia, 1997-1998; NASA Goddard Space Flight Center (GSFC) 1998-2000) were on radiation mechanisms of pulsars. He started to work on theories of gamma-ray bursts (GRBs) in 2000 when he moved to Penn State University as a postdoc. He moved to UNLV in 2004, the same year when the NASA Swift mission was launched (with which he is affiliated). He spent most of his time understanding the physical mechanism of GRBs and other high-energy transients until recently when he shifts focus to FRBs, whose phenomenology and physical mechanisms mimic either pulsars or GRBs but also with significant differences. He is currently leading the FAST FRB Key Project to observationally study FRBs. One interesting experience was his 3-month visit to Australia back in 1998 hosted by Dick Manchester and Mathew Bailes (who just joined the faculty at Swinburne). His assigned job was to search for single radio pulses from Parkes archives. He made some progress but quit after receiving the offer from NASA GSFC. Later he was told that there were no FRBs from that archival data, so he was not particularly regretful for leaving the field for a substantial time.

REFERENCES

Anna-Thomas, R. et al. 2022, Science, submitted (arXiv: 2202.11112)

Beloborodov, A. M. 2021, ApJ, 922, L7

Falcke, H. & Rezzolla, L. 2014, A&A, 562, A137

Li, D. et al. 2020, Nature, 598, 267

Luo, R. et al. 2020, Nature, 586, 693

Moroianu, A. et al. 2022, Nature Astronomy, submitted

Qu, Y., Kumar, P. & Zhang, B. 2022, MNRAS, 515, 2020

Xu, H. et al. 2022, Nature, in press (arXiv: 2111.11764)

Zhang, B. 2014, ApJ, 780, L21

Zhang, B. 2012, ApJ, 925, 53

Zhang, Y. K.,et al. 2022, RAA, submitted

Zhou, D. J.,et al. 2022, RAA, submitted

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