Fast Radio Bursts’ Emission Mechanism: Implication from Localization

Maxim Lyutikov1,2

1 Department of Physics and Astronomy, Purdue University, 525 Northwestern Avenue, West Lafayette, IN 47907-2036, USA
2 Department of Physics and McGill Space Institute, McGill University, 3600 University Street, Montreal, QC H3A 2T8, Canada

Received 2017 January 17; revised 2017 February 6; accepted 2017 February 7; published 2017 March 24

Abstract

We argue that the localization of the repeating fast radio bursts (FRBs) at ~1 Gpc excludes a rotationally powered type of radio emission (e.g., analogs of Crab’s giant pulses coming from very young energetic pulsars) as the origin of FRBs.

Key words: pulsars: general – radiation mechanisms: general – stars: neutron

1. Introduction

Fast radio bursts (FRBs; Lorimer et al. 2007; Keane et al. 2012; Thornton et al. 2013; Kulkarni et al. 2014; Spitler et al. 2014, 2016) are a recently identified type of transient radio emission. The recent localization of the host galaxy of the repeating FRB 121102 (the repeating FRB below) by Chatterjee et al. (2017) establishes sources of FRBs as cosmological (and not only extragalactic) objects. The host galaxy is located at the distance $D \sim 1$ Gpc.

The power and the (upper limit on the intrinsic) duration of FRBs require neutron-star-like energy densities of the magnetic field in the emission region (Lyutikov et al. 2016a). In the case of FRB 121102, the instantaneous (isotropic-equivalent) luminosity $L_{\text{FRB}}$ is

$$L_{\text{FRB}} = 4\pi D^2 (\nu F_{\nu}) \approx 10^{42} F_{12} D_{\text{Gpc}}^2 \text{erg s}^{-1},$$

where $F_{\nu}$ is the flux in Jansky and $\nu$ is the observation frequency. Taking the duration of the bursts $\tau \approx 1$ ms $\equiv \tau_3$ as an indication of the emission size, the equipartition magnetic field energy density at the source is

$$B_{\text{eq}} = \sqrt{8\pi \nu F_{\nu} D / c^2} = 3 \times 10^{8} \tau_3^{-1} \text{G}.$$ (2)

As the estimate (2) is the lower estimate on the magnetic field at the source, this narrows down the location of the emission region to magnetospheres of neutron stars.

The brightness temperature

$$T_b \approx \frac{2\pi D^2 F_{\nu} \Delta \Omega}{\nu^2 \tau^2} \frac{4\pi}{\nu^2} \approx 5 \times 10^{35} \text{K}$$

(3)

clearly implies a coherent mechanism.

Relativistic motion modifies somewhat the above estimates for the rest-frame magnetic field and the brightness temperature. If the source is moving with Lorentz factor $\Gamma$, the brightness temperature in the source rest frame is smaller by $\sim \Gamma^2$—the conclusion that the emission must be coherent remains solid. As for the lower limit on the magnetic field at the source (Equation (2)) since $\nu F_{\nu} \propto \Gamma^4$ and $\tau \propto \Gamma^{-2}$, the rest-frame magnetic field can be smaller than the estimate (2) by a factor $\Gamma^2$. Only fairly high bulk Lorentz factor $\Gamma \gtrsim 10$ may bring the estimate (2) to fields, e.g., of white dwarfs, but we do not expect such large Lorentz factors in the matter-dominated magnetospheres of white dwarfs.

In addition, the estimate of the wave intensity parameter

$$a = \frac{eE}{m_e c \omega} \approx 10^5 \gg 1,$$ (4)

where $E = \sqrt{L_{\text{FRB}} / (c^3 \tau^2)}$ is the typical electric field in the wave at the emission site and $\omega = 2\pi \nu$ is the observed frequency (Luan & Goldreich 2014), require presence of strong magnetic field with $\omega_B \gg \omega$, so that the correct definition of the intensity parameter (4) is (Lyutikov et al. 2016a)

$$a_B = \frac{eE}{m_e c \omega_B} \approx 1,$$ (5)

where $\omega_B = E_B / (m_e c)$ is the corresponding cyclotron frequency.

Thus, magnetospheres of neutron stars are the most promising loci of the FRBs emission generation (Popov & Postnov 2010; Pen & Connor 2015; Cordes & Wasserman 2016; Lyutikov et al. 2016a). Identification of FRBs with neutron star and the repetitiveness as evidence against catastrophic events (collapse, coalescence, etc.) leave two possible types of production of radio emission: (i) hypothetical radio emission accompanying giant flares in magnetars (Lyutikov 2002, Popov & Postnov 2010; Keane et al. 2012; Lyubarsky 2014; Pen & Connor 2015; Katz 2016); (ii) giant pulse (GP) analogs emitted by young pulsars (Lundgren et al. 1995; Soglasnov et al. 2004; Popov & Stappers 2007); see discussions by Lyutikov et al. (2016a), Cordes & Wasserman (2016), and Connor et al. (2016). These two possibilities rely on different source of energies for FRBs: strong magnetic fields in the case of magnetars and rotational energy in the case of GPs.

2. Not GPs from Young Energetic Pulsars

Lyutikov et al. (2016a) argued that if the FRBs are analogs of GPs but come from young (ages tens to hundreds years) pulsars with a Crab-like magnetic field, then the required initial periods need to be in the few millisecond range—a reasonable assumption for $D \lesssim$ few hundreds Mpc. Identification of the FRB host with a galaxy at $D = 1$ Gpc makes this possibility unlikely, as we discuss next.

For a Crab pulsar the peak GP fluxes $F_\nu$ exceed mega-Jansky (Hankins et al. 2003; Soglasnov 2007). The observed fluxes from the repeating FRB were in the hundreds milli-Jansky range. Thus, it is required that the intrinsic GP power at the
FRB source be

$$\frac{L_{\text{FRB}}}{L_{\text{GP}}} \approx 2.5 \times 10^5.$$  \hspace{1cm} (6)

Scaling the FRB power with the spin-down power (we note that this is not the case for the bulk of the pulsar population; Manchester et al. 2005) then puts constraints on the magnetic field and the spin period of the FRB source:

$$\left( \frac{B_{\text{FRB}}}{B_{\text{Crab}}} \right) \left( \frac{P_{\text{FRB}}}{P_{\text{Crab}}} \right)^{-2} \approx 500$$  \hspace{1cm} (7)

($B$ and $P$ are corresponding surface magnetic fields and periods). Thus, a Crab-like pulsar needs to spin at 1.5 ms, while a magnetar-like neutron star with a quantum magnetic field on the surface needs to spin at $\sim 5$ ms. Though these are physically allowed values, as we show below, the corresponding spin-down time is very short, contradicting the observed constancy of the repeating FRB over the few years of observations.

One possible caveat is that the FRB source can have higher efficiency in converting spin-down power into radiation than Crab’s GPs (for Crab the instantaneous efficiency can reach $10^{-2}$). Parameterizing the observed flux as

$$\nu F_{\nu} = \frac{\eta}{4\pi D^2} L_{\text{sd}},$$  \hspace{1cm} (8)

where $L_{\text{sd}}$ is the spin-down luminosity, an $\eta \leq 1$ is the conversion efficiency. The conversion efficiency $\eta$ is smaller than unity since the energy associated with an FRB should originate in the magnetospheres of NSs (and not, e.g., in the crust—this would involve much longer timescales, $\sim 100$ ms—the shear timescale through the crust). Also, pulsar glitches do not produce any considerable perturbation to the magnetosphere. There is no way to “store” more energy in the magnetosphere.

The longest possible spin-down time is then

$$\tau_{\text{SD}} = \frac{\pi I_{\text{SS}}}{2 D^2 \nu F_{\nu} P_{\text{min}}^2} \approx 600 \eta \text{ years}$$  \hspace{1cm} (9)

for $F_{\nu} = 1$ Jy and the minimal period of $P_{\text{min}} = 1$ ms. (For a given FRB luminosity $L_{\text{FRB}}$, scaled with spin-down power, the longest spin-down time is for shortest periods and, correspondingly, smallest magnetic fields). The longest possible spin-down timescale (9) is barely consistent with the constant value of the properties of the repeating FRB over a period of a few years—that would require an unrealistically high conversion efficiency of $\eta \rightarrow 1$.

Another constraint comes from the constant values of the dispersion measure (DM) over a few years (Chatterjee et al. 2017; Tendulkar et al. 2017). For the repeating FRB approximately half of the DM contribution comes from the local plasma, $D_{\text{DM}} \approx 100$. This is consistent with contribution from a dwarf galaxy, thus excluding a large contribution from the circumburst medium (Tendulkar et al. 2017). On the other hand, as we argued above, the typical timescale of the source is very short, a supernova (SN) remnant should still be present. If DM is associated with an expanding SN shell, then it should sharply decrease with time, $D \propto t^{-2}$ (Lyutikov et al. 2016a; Piro 2016). Since no DM changes are seen, this further excludes young rotationally powered pulsars as FRB sources.

3. Discussion

The location of the repeating FRB at $\sim 1$ Gpc (an order of magnitude further away than what was a fiducial model in Lyutikov et al. 2016a), combined with a very steady value of DM, virtually excludes FRBs as analogs of Crab GPs. The allowed parameter region is very narrow: only an extremely efficient conversion of the rotational energy into radio waves, $\eta \approx 1$, combined with millisecond period at birth and a very specific range of ages 100 years $\sim t < 500$ years (the lower limit come from the requirement of nearly constant DM, while the upper limit comes from the spin-down age; Equation (9)) can account for fluxes, duration, distance to FRB, and the constant value of DM.

The alternative model—hypothesised generation of high brightness coherent radio emission during the initial stages of magnetar flares (e.g., Lyutikov 2003)—is only marginally better suited to explain FRBs. Briefly, we expect that during the initial explosive stages of the current sheet formation in magnetar magnetospheres the inductive electric fields accelerate particles (somewhat similar to acceleration mechanism discussed by Lyutikov et al. 2016b), producing distributions that are unstable to generation of coherent emission. The peak luminosity of the flare from SGR 1806–20 was $10^{47}$ erg s$^{-1}$ (Palmer et al. 2005). Thus, efficiency of $\sim 10^{-5}$ between radio and X-rays is sufficient to power an FRB. However, the corresponding signal from a magnetar at 10 kpc would produce an FRB in the giga-Jansky range. This may contradict the non-detection of the SGR 1806–20 flare by Parkes (Tendulkar et al. 2016). We encourage an observational campaign to detect possible radio burst contemporaneous with magnetar bursts and flares. Another puzzling property of FRBs within the frameworks of both models is a very high and constant in time local DM.

I would like to thank members of McGill Space Institute (in particular Victoria Kaspi and Shriharsh Tendulkar), Ue-Li Pen, and Sergey Popov for discussions.

This work was supported by NSF grant AST-1306672 and DoE grant DE-SC0016369.

References

Chatterjee, S., Law, C. J., Wharton, R. S., et al. 2017, Natur, 541, 58
Connor, L., Sievers, J., & Pen, U.-L. 2016, MNRAS, 458, L19
Cordes, J. M., & Wasserman, I. 2016, MNRAS, 457, 232
Hankins, T. H., Kern, J. S., Weatherall, J. C., & Eilek, J. A. 2003, Natur, 422, 141
Katz, J. I. 2016, ApJ, 826, 226
Keane, E. F., Stappers, B. W., Kramer, M., & Lyne, A. G. 2012, MNRAS, 425, L71
Kulkarni, S. R., Ofek, E. O., Neill, J. D., Zheng, Z., & Juric, M. 2014, ApJ, 797, 70
Lorimer, D. R., Bailes, M., McLaughlin, M. A., Narkevic, D. J., & Crawford, F. 2007, Sci, 318, 777
Luan, J., & Goldreich, P. 2014, ApJL, 785, L26
Lundgren, S. C., Cordes, J. M., Ulmer, M., et al. 1995, ApJ, 453, 433
Lyubarsky, Y. 2014, MNRAS, 442, L9
Lyutikov, M. 2002, ApJL, 580, L65
Lyutikov, M. 2003, MNRAS, 346, 540
Lyutikov, M., Burzawa, L., & Popov, S. B. 2016a, MNRAS, 462, 941
Lyutikov, M., Sironi, L., Komissarov, S., & Porth, O. 2016b, arXiv:1603.05731
Manchester, R. N., Hobbs, G. B., Teoh, A., & Hobbs, M. 2005, AJ, 129, 1993
Palmer, D. M., Barthelmy, S., Gehrels, N., et al. 2005, Natur, 434, 1107
Pen, U.-L., & Connor, L. 2015, ApJ, 807, 179
Piro, A. L. 2016, ApJL, 824, L32
Popov, M. V., & Stappers, B. 2007, A&A, 470, 1003
Popov, S. B., & Postnov, K. A. 2010, in Evolution of Cosmic Objects through their Physical Activity, ed. H. A. Harutyunian, A. M. Mickaelian, & Y. Terzian (Yerevan: NAS RA), 129
Soglasnov, V. 2007, in WE-Heraeus Seminar on Neutron Stars and Pulsars 40 Years after the Discovery, ed. W. Becker & H. H. Huang (Garching bei München: Max Planck Institut für extraterrestrische Physik), 68
Soglasnov, V. A., Popov, M. V., Bartel, N., et al. 2004, ApJ, 616, 439
Spitler, L. G., Cordes, J. M., Hessels, J. W. T., et al. 2014, ApJ, 790, 101
Spitler, L. G., Scholz, P., Hessels, J. W. T., et al. 2016, Natur, 531, 202
Tendulkar, S. P., Bassa, C. G., Cordes, J. M., et al. 2017, ApJ, 834, L7
Tendulkar, S. P., Kaspi, V. M., & Patel, C. 2016, ApJ, 827, 59
Thornton, D., Stappers, B., Bailes, M., et al. 2013, Sci, 341, 53