Fast Radio Bursts counterparts in the scenario of supergiant pulses

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ABSTRACT

We discuss identification of possible counterparts and persistent sources related to Fast Radio Bursts (FRBs) in the framework of the model of supergiant pulses from young neutron stars with large spin-down luminosities. In particular, we demonstrate that at least some of sources of FRBs can be observed as ultraluminous X-ray sources (ULXs). At the moment no ULXs are known to be coincident with localization areas of FRBs. We searched for a correlation of FRB positions with galaxies in the 2MASS Redshift survey catalogue. Our analysis produced statistically insignificant overabundance ($p$-value $\approx 4\%$) of galaxies in error boxes of FRBs. In the very near future with even modestly increased statistics of FRBs and with the help of dedicated X-ray observations and all-sky X-ray surveys it will be possible to decisively prove or falsify the supergiant pulses model.

Key words: pulsars: general – X-rays: binaries

1 INTRODUCTION

Fast radio bursts (FRBs) comprise a new emerging class of radio transients (see a review in Katz 2016). At the moment, 17 sources are known (see the catalogue in Petroff et al. 2016). They are characterised by short durations ($\sim$ few msec), and large values of dispersion measure (DM) which are much larger than the expected Galactic contribution (Cordes & Lazio 2002). If these large values were obtained during propagation through extragalactic medium, this would firmly put FRBs at cosmological distances, $d > 1$ Gpc, and would correspond to gigantic energy outputs (just in radio waves!) of these events:

$$L_r \sim 10^{42} \left( \frac{S_{\text{peak}}}{\text{Jy}} \right) \left( \frac{\Delta \nu}{1.4 \text{GHz}} \right) \left( \frac{d}{1 \text{ Gpc}} \right)^2 \text{erg s}^{-1}. \quad (1)$$

$$E_r \sim 10^{39} \left( \frac{\tau}{1 \text{msec}} \right) \left( \frac{d}{1 \text{ Gpc}} \right)^2 \left( \frac{L_{\text{iso}}}{10^{42} \text{erg s}^{-1}} \right)^3 \text{erg}. \quad (2)$$

Here $d$ is the distance to the source, $L_r$ and $E_r$ are the radio luminosity and energy output under assumption of isotropy correspondingly, $S_{\text{peak}}$ – peak flux, $\tau$ is the duration of the burst, and $\Delta \nu$ is the range of frequencies which for estimates we set equal to the typical frequency of observation of FRBs – 1.4 GHz.

Short duration of these events implies that size of the active region is very small, $\lesssim 10^8$ cm, which makes neutron stars-related phenomena the most plausible candidates for explanation. Still, the FRBs could be a heterogeneous phenomena, consisting of several sub-populations for which different mechanisms of burst emission might be applied.

Many models have been proposed to explain the nature of FRBs (see, for example, references in Katz 2016). Naturally, the majority of these scenarios are related to neutron stars (NSs). Among them several broad categories can be distinguished:

- FRBs are due to collapse of a supramassive NS to a black hole (Falcke & Rezzolla 2014).
- FRBs are generated during NS-NS mergers (Pshirkov & Postnov 2010; Totani 2013).
- FRBs are produced in (or after) magnetar hyperflares (Popov & Postnov 2010; Lyubarsky 2014).
- FRBs are phenomena akin to the Crab giant pulses (GPs). Very young fast-rotating pulsars (PSRs) with ages less than $\sim$100 years can potentially demonstrate analogues of GPs which are $10^4 - 10^5$ more luminous than in the Crab pulsar (Cordes & Wasserman 2016; Connor et al. 2016b). Such hypothetical events are dubbed “supergiant pulses”. These flares could be observed as FRBs on Earth. In this scenario, most of DM is accumulated in the very vicinity of these events.
of pulsar in its supernova remnant, and that allow to put FRBs at somewhat smaller distances: \( d \lesssim 100 - 200 \) Mpc. All other models assume cosmological distances \( \gtrsim 1 \) Gpc.

The first among mentioned scenarios can hardly provide a reasonable estimate for the rate of events inferred from the observations. The energy output is highly uncertain. In addition, as FRBs are not shown to be coincident with supernova (SN). Altogether, this means that the model meets some severe restrictions.

The model with coalescing NSs could easily meet necessary energetic requirements, but also have serious difficulties explaining rate of FRBs and repetitive bursts. At the end of 2015 the magnetar model was considered as nearly the best, but still any confirmations based on observations of Galactic magnetars are lacking (i.e., up to date there are no detections of radio bursts coincident with high energy flares; see Tendulkar et al. 2016 and discussion in Katz 2016).

So, below we mainly focus on the model of supergiant pulses.\(^1\) In this note we will briefly analyse potentially testable predictions for multwavelength observations of the sources of FRBs in this scenario.

## 2 FRBS BY ENERGETIC RADIO PULSARS

Lyutikov et al. (2016) developed further the model in which FRBs are due to supergiants pulses of PSRs (Connor et al. 2016b; Cordes & Wasserman 2016). In this section we briefly describe the main features of this scenario.

In this model, a FRB is emitted by a very energetic PSR. Expected spin-down luminosity, \( \dot{E} \), are \( \sim 10^{43} \) erg s\(^{-1}\). The emission mechanism is supposed to be similar to the mechanism of GPs, but the maximal luminosity is scaled linearly with \( \dot{E} \) (note, that FRBs can be longer than GPs; as FRBs are widened due to scattering, and it is difficult to derive their intrinsic duration. So, scaling of the total energy release is a more complicated subject). Then, it is possible to obtain radio pulses \( \sim 10^5 \) stronger than GPs of the Crab. Such events might explain properties (peak fluxes) of known FRBs, if observed from 100-200 Mpc.

These distances guarantee roughly isotropic distribution of sources in the sky. At the moment the observational data are in an agreement with such isotropy. Still, we note, that unless the statistics is significantly higher, all analyses of isotropy are strongly limited by a small number of known sources. If sources are indeed inside \( \sim 200 \) Mpc radius sphere, then it can be possible in the near future to probe deviation from the isotropy due to still slightly inhomogeneous distribution of galaxies in this volume (see, for example, Colless et al. 2001).

Mostly, the DM is due to a still dense shell (supernova remnant) around the NS. Then, expected ages of such PSRs are about few tens of years. For estimates below we use as a typical value the age 30 years.

Note, that as in the model with supergiant pulses and in the model with magnetar flares FRBs are related to young NS, sources might be located in regions of intense starformation. Then, significant DM can be partially due to the interstellar medium in the local surroundings. In any case, absence of FRBs with low DM requires some “guaranteed” DM, either due to a SNR, or due to intergalactic medium.

Calculations (see Lyutikov et al. 2016) show that it is possible to explain the estimated FRBs rate \( \sim 10^6 \) per day by the population of young \( \lesssim \) few tens of years) energetic PSRs within 100-200 Mpc from the Sun assuming that the repetition rate is \( \lesssim 1 \) per day, in correspondence with observations. This estimate is based on the core-collapse SN rate \( \sim 3 \times 10^{-4} \) yr\(^{-1}\) Mpc\(^{-3}\) (Dahlen et al. 2012).

The supergiant pulses scenario predicts that FRBs should repeat quite frequently. Given that all FRBs were observed with high signal-to-noise ratio (Petroff et al. 2016), and that GP rate falls very quickly with increasing \( L \), it is natural to expect fainter but much more frequent repetitive FRBs. The FRB 121102 can be an example of such behaviour (Spitler et al. 2016).

We can expect to have \( \gtrsim 10^5 \) large galaxies within this volume. This corresponds to about one source per 10 galaxies. Near-by population of galaxies is relatively well studied, and if sources of FRBs remain bright at some energy range even between the bursts, then we can hope to identify them in catalogues, archival data, or dedicated observations.

Young PSRs with large \( \dot{E} \) are known to be bright X-ray sources. According to Possenti et al. (2002) X-ray luminosity of such a source can be estimated as: \( L_X = 10^{-15.3} \dot{E}^{1.34} \). In addition, some fraction of total energy losses might be re-emitted by a pulsar wind nebula (PWN).

A shell around the PSR relatively quickly, — within few years, — becomes transparent for X-rays (Murase et al. 2016). So, at the ages required in the scenario by Lyutikov et al. (2016) a bright (possibly ultraluminous) X-ray source might be observed.

In this respect, what would be the observational consequences of the supergiant PSR burst scenario? How presence of several thousand energetic \( (\dot{E} \sim 10^{33} \text{ erg s}^{-1}) \) in 200 Mpc radius sphere (given 100% fraction of young pulsar-related FRBs) can be probed? We suggest that it might result in appearance of many ultraluminous X-ray sources (ULXs). This conclusion seems to be unavoidable in this framework, and we discuss it in the following section.

## 3 ULXS AS CONTERPARTS OF YOUNG ENERGETIC PULSARS

A young PSR might have an X-ray luminosity:

\[
L_X \approx 2 \times 10^{42} \left( \frac{\dot{E}}{10^{43} \text{ erg s}^{-1}} \right)^{1.34} \text{ erg s}^{-1},
\]

(see Possenti et al. 2002). However, this relation is not probed for very high values of \( \dot{E} \), and so its usage is just an extrapolation. Most probably, \( L_X \) does not grow that fast with \( \dot{E} \) for large values (still, for sure we expect to have a very bright X-ray sources for large rotational energy losses). On the other hand, significant additional X-ray emission can appear due to a PWN (Kargaltsev et al. 2013). Perna & Stella (2004) suggested that some of ultraluminous X-ray sources (ULXs) can be young energetic

\(^1\) When this paper was ready for submission, Lyutikov and Lorimer submitted an e-print (arXiv: 1605.01468) in which they addressed the question of contemporaneous counterparts of FRBs in the framework of a magnetar flare.
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4 FUTURE SEARCHES FOR PERSISTENT COUNTERPARTS

In this section we discuss several issues related to the FRB-ULX connection.

4.1 Possible XMM-Newton observations

Identification of host galaxies of FRBs is complicated as their positions are not well-known. Most of the bursts have been discovered at the Parkes telescope. Then, the uncertainty in position is about the size of the beam of Parkes. Full beam width on half maximum amplitude is \( \approx 14-15 \) arcmin (Petroff et al. 2016). Note, that the field of view of the EPIC instrument onboard XMM-Newton is about 30' in diameter (Turner et al. 2001). If FRBs are mostly (or at least partly) due to supergiant pulses of energetic PSRs, then we can expect to find an X-ray source with flux \( f \approx 8 \times 10^{-13} (L_X/10^{42} \text{ erg s}^{-1}) d_{100}^{-2} \text{ erg cm}^{-2} \text{ s}^{-1} \).

In the framework of the scenario developed by Lyutikov et al. (2016) FRB luminosity is \( L_r = \eta E \), where \( \eta \approx 0.01 \). FRBs with different observed peak fluxes are nearly uniformly distributed in distances, and DM is a poor indicator of distance to the source. According to Possenti et al. (2002) \( L_X \sim E^{1.34} \). Then it is possible to find a relatively bright (in terms of the flux) ULX coincident with a bright FRB in a relatively distant galaxy. Moreover, if peak flux of FRBs is not correlated with the distance (or correlates very weakly), then brighter (in terms of flux) ULXs can be found in more distant galaxies. This can be illustrated as follows.

For a typical FRB with peak flux \( S_{\text{peak}} = 1 \text{ Jy} \) we obtain radio luminosity:

\[
L_r = 1.7 \times 10^{40} (S_{\text{peak}}/1 \text{ Jy}) (d/100 \text{ Mpc})^2 \text{ erg s}^{-1}.
\]

Then, rotational energy losses are:

\[
E = 1.7 \times 10^{42} (S_{\text{peak}}/1 \text{ Jy}) (d/100 \text{ Mpc})^2 (\eta/0.01)^{-1} \text{ erg s}^{-1}.
\]

Using the relation from Possenti et al. we obtain the X-ray luminosity:

\[
L_X = 1.8 \times 10^{41} (S_{\text{peak}}/1 \text{ Jy})^{1.34} \times (d/100 \text{ Mpc})^{2.68} (\eta/0.01)^{-1.34} \text{ erg s}^{-1}.
\]

And so, the X-ray flux is:

\[
f_X = 1.5 \times 10^{-13} (S_{\text{peak}}/1 \text{ Jy})^{1.34} \times (d/100 \text{ Mpc})^{0.68} (\eta/0.01)^{-1.34} \text{ erg cm}^{-2} \text{ s}^{-1}.
\]

For large distances we obtain higher \( f_X \) for a given \( S_{\text{peak}} \), for smaller — weaker. If a source with peak flux 1 Jy is at 10 Mpc, then \( f_X = 3.2 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \). Correspondently, for 200 Mpc we have \( f_X = 2.5 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \).

Then, a limit is determined by closer sources.\(^3\) Note, that the applied relation \( L_X \) vs. \( E \) can not be valid for large luminosities.

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\(^2\) We use a more conservative estimate for the positional accuracy which is double of the FWHM of a Parkes beam.

\(^3\) Non-
4.2 Search for FRBs in “supernova factories”

Inside $\lesssim 50$ Mpc there are few galaxies with extreme values of starformation rate and supernova rate. In particular, we note Arp 299 (Neff et al. 2004), and NGC 3256 (Lipari et al. 2004).

The rate of SNae in these galaxies is $\sim 1$ per year. Then, even if just $1/10$ of young pulsars are energetic enough to produce a detectable FRB from $d \sim 40$ Mpc, then we can expect several of such sources in each galaxy. With the rate of repetition $\sim$ once per day, it is worth trying to monitor these galaxies in radio. Identification of an ULX, however, would be very problematic in such cases due to crowding of X-ray sources.

4.3 Sources in local starforming galaxies

Inside $\lesssim 4$ Mpc most of starformation is related to just four galaxies: M82, M83, NGC 253, NGC 4945 (Heckman 1998). Typically, SN rate in each of these galaxies is higher than in the Milky way by a factor of a few (up to 10, see data and references in Popov 2005).

We can expect few PSRs with ages $\lesssim 30$ yrs in each of these galaxies. Some of them can be energetic enough to produce detectable FRBs. As galaxies are near-by, identification of ULXs would not be a very difficult task.

Note, that no ULXs with $L_X > 10^{41}$ erg s$^{-1}$ have been found in these galaxies. Then we can suspect that potential sources have smaller $E$, and so produce radio bursts with luminosities smaller that those of classical FRBs. Still, radio monitoring is worthwhile due to proximity of these galaxies.

4.4 Bursts from M31

M31 is the closest large galaxy. Recently Rubio-Herrera et al. (2013) reported discovery of several millisecond radio bursts from it. No periodicity have been found (so, the interpretation based on radio pulsars or RRATs is not viable), however, some sources can be repetitive. Popov & Postnov (2013) suggested that this flares can be weak relatives of FRBs, originating from the same type of sources which demonstrate activity in different ranges of released energy (in the particular model these two types of activity are hyperflares of magnetars and their usual weak bursts).

A similar interpretation can be made in the case of supergiant pulses. I.e., we observed analogues of FRBs from more numerous PSRs with smaller $E$, which cannot produce strong bursts. Then, search for weak FRBs from local galaxies can be fruitful (or can put important constraints on the model of supergiant pulses).

4.5 Future observations

It is expected that statistics of FRBs can be greatly increased in 1-2 years (Connor et al. 2016a; Keane & SUPERB Collaboration 2016). This might be due to several new instruments. UTMOST is already working (Caleb et al. 2016), and it is expected that it is going to contribute to the increase of the FRB statistics with the detection rate $\sim 1$ per 1-2 weeks. Another telescope — CHIME (Bandura et al. 2014) — is expected to start gathering data very soon and reach the rate up to $\sim 1$ per day, if at lower frequencies FRBs are well-visible.

In the fall of 2016 the Five hundred meter Aperture Spherical Telescope (FAST, Nan et al. 2011) might be completed. It is expected that this instrument will detect one new FRB in a week of operation (Li et al. 2016).

In not-so-close future SKA will become extremely effective, detecting nearly a FRB each hour in the final configuration (Macquart et al. 2015; Keane & SUPERB Collaboration 2016). By itself, new radio data can be used to probe many proposed models of FRBs. For example, in the scenario with supergiant pulses we expect that with $\sim 100$ sources we can easily reach a statistically significant level of correlation with local galaxies. New radio observations can be complemented by a new sensitive all-sky X-ray survey by eROSITA onboard Spektrum-Roentgen-Gamma (Predehl et al. 2011). This would make testing this model even easier. And if the model is correct, than we can expect many associations of FRBs with ULXs due to new observations.

5 SUMMARY

The supergiant pulses model of FRBs can be tested on the base of a direct identification of sources, because in this framework they are young energetic pulsars residing quite close to us, $d < 200$ Mpc. Large spin-down luminosity of these pulsars, $E \sim 10^{43}$ erg s$^{-1}$, will lead to emergence of bright counterparts at various frequencies. The pulsars (and also, possibly, their PWNs, see Kargaltsev et al. 2013) might be luminous X-ray sources and eventually can manifest themselves as ULXs with luminosities that can even overcome the brightest HMXBs, $L_X > 10^{41}$ erg s$^{-1}$. Unfortunately, at the moment no FRB are known in the regions observed by the XMM-Newton X-ray observatory. There are two natural avenues to pursue: first, dedicated observations at several directions, coinciding with FRB localizations, can be performed; second, one can search for unusual ULXs in archival data.

As already stated above, FRBs can also be rather bright persistent sources in radio waveband, and this is crucial for discrimination between young pulsars and HMXBs$^4$; one will not expect any sizeable radio-emission from HMXBs, beside rare cases of microquasars, which can be mostly filtered out due to their variability. It can also be the case when we are trying to discriminate against background AGNs that can mimic our sought sources. Also, after accurate pin-pointing of candidate position with X-ray and radio observations, it is possible to search for counterparts at other frequencies – in optics, IR, or UV.

Finally, the conclusion that the FRBs should be local phenomena ($d < 200$ Mpc) can be tested even if these

$^4$ Given that we are not dealing with the extreme case of ULX with $L_X > 10^{41}$, as HMXBs with such luminosity might be extremely rare, or even absent.
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We correlated FRB positions with bright galaxies from the 2MRS catalogue. We found 5 pairs FRB-galaxy with distance less than 15′, and 1.87 coincidences were expected by chance, giving a Poissonian probability \( p \sim 4\% \). With even modest increase in total FRB number the fraction of local population will be estimated (or, seriously constrained) in the very near future.

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