ABSTRACT

Lyutikov (2002) predicted “radio emission from soft gamma-ray repeaters (SGRs) during their bursting activity”. Detection of a Mega-Jansky radio burst in temporal coincidence with high energy bursts from a Galactic magnetar SGR 1935+2154 confirms that prediction. Similarity of this radio event with Fast Radio Bursts (FRBs) suggests that FRBs are produced within magnetar magnetospheres. We demonstrate that SGR 1935+2154 satisfies the previously derived constraints on the physical parameters at the FRBs’ loci. Coherent radio emission is generated in the inner parts of the magnetosphere at \( r < 100R_{\text{NS}} \). The radio emission is produced by the yet unidentified plasma emission process, occurring during the initial stages of reconnection events.

1. Introduction

Detection of Mega-Jansky radio burst from a galactic magnetar SGR 1935+2154 by CHIME and STARE2 (ATel 13681, 13681), in temporal coincidence with high energy bursts observed by Integral (GCN 27666, ATel 13685), AGILE (ATel 13686), Konus-Wind (GCN 27669, ATel 13688), and Insight-HXMT (ATel 13687) identifies the magnetosphere of “classical” magnetar as the site of this event. Many features of this radio burst resemble Fast Radio Bursts (FRBs), suggesting magnetospheres of magnetars as FRB production sites (for review of FRBs phenomenology see Popov et al. (2018); Platts et al. (2019); Petroff et al. (2019); Cordes & Chatterjee (2019), and the catalogue in Petroff et al. (2016) \(^1\); for reviews on magnetars see Turolla et al. (2015); Gourgouliatos & Esposito (2018) and the catalogue in Olausen & Kaspi (2014) \(^2\).

The observations are consistent with the concept that radio and X-ray bursts are generated during reconnection events in the magnetars magnetospheres, as suggested by Lyutikov (2002). Conceptually, magnetar radio/X-ray flares are similar to Solar flares, initiated by the magnetic field instabilities in the magnetars’ magnetospheres. (Radio emission from magnetars was further

\(^1\)URL: http://frbcat.org/
\(^2\)URL: http://www.physics.mcgill.ca/ pulsar/magnetar/main.html
discussed by Eichler et al. (2002); Lyutikov (2003, 2006a, 2015); Benz & Güdel (2010) discuss the electromagnetic signatures of Solar flares.)

Lyutikov (2002) suggested two spectral properties of magnetars’ radio emission, one that was confirmed and another relevant for the current problem. First, the prediction was that magnetars will be brighter at higher radio frequencies since in twisted magnetospheres (Thompson et al. 2002a) the density and the plasma frequency can be much larger than in rotationally-powered pulsars (Goldreich & Julian 1969). This was later confirmed: at tens of GHz magnetars are the brightest, though variable, pulsars (Camilo et al. 2006; Olausen & Kaspi 2014; Kaspi & Beloborodov 2017). Second, a downward frequency drift was predicted, by analogy with Solar type-III radio bursts. This was not (yet?) seen in magnetars, but high-to-low frequency drifting features were indeed observed in the spectra of the repeating FRBs (Hessels et al. 2019). The drifts are then the FRBs’ analogues of Solar type-III radio burst (but not in a sense of a particular emission mechanism, Lyutikov 2020b). Related concept is the radius-to-frequency mapping in radio pulsars (Manchester & Taylor 1977; Phillips 1992).

The plasma parameters required to produce FRBs are extreme, even when compared with brightest pulses from rotationally-powered pulsars (Lyutikov & Rafat 2019). Lyutikov & Rafat (2019) argued that the requirements on plasma properties can be generally satisfied in magnetars’ magnetospheres. In this paper we apply the more general conditions discussed by Lyutikov & Rafat (2019) to the particular case of radio bursts from SGR 1935+2154.

To be clear, the term “magnetar” is used in two astrophysically separate settings: (i) powerful X-ray emitters, SGRs and AXPs, we term them “classical magnetars” (eg Thompson & Duncan 1993, 1995; Thompson et al. 2002b; Kaspi & Beloborodov 2017); (ii) fast pulsar with high magnetic field and high wind power, we term them “millisecond magnetars” (Usov 1992; Lyutikov 2006c; Metzger et al. 2008). In the former case the radiative energy comes from the energy of the magnetic field, while in the latter case from its rotational energy (the strong magnetic field just serves to quickly transform the rotational energy into the wind). FRBs are not rotationally powered “fast-rotation pulsar with high magnetic field”-magnetar concept, but are magnetically-powered “classical” magnetars sources. We also note that long term periodicity observed in some FBRs (The CHIME/FRB Collaboration et al. 2020; Rajwade et al. 2020) is consistent with mildly powerful neutron star, not a millisecond magnetar-type (Lyutikov et al. 2020, wrote “The observations are consistent with magnetically powered radio emission originating in the magnetospheres of young, strongly magnetized neutron stars, the classical magnetars.”).

2. Observational time-line and best contemporaneous interpretation of FRBs

As the origin of FRBs is being settled down, let us have a quick look at the observational time line and the best contemporaneous interpretations, as viewed now:
• “Early years”: from Lorimer et al. (2007) to Thornton et al. (2013). Time of many hypothesis, no leaders. Among others, merging neutron stars are discussed (see early discussion of transients from NS-NS mergers by Hansen & Lyutikov 2001; Lyutikov 2011), and later proposals particularly for FRBs by Totani (2013); Falcke & Rezzolla (2014). The main argument for NS-NS merges was that the active stage lasts $\sim R_{NS}^3/(GM_{NS})^{1/2} \sim \text{milliseconds}$, matching FRB duration. Magnetar origin (as well as scaling of Crab giant pulses with rotational energy losses) is proposed, but mostly ignored (Popov & Postnov 2007).

• “High rates years”: from Thornton et al. (2013) to Spitler et al. (2016). Rates, $\sim 10^4$ per sky per day, are well in excess of NS-NS merger rates; hence FRBs most likely involve non-destructive events. Burst energetics requires NS-type magnetic fields (Lyutikov et al. 2016). Magnetically powered magnetar flares (Popov & Postnov 2013) or rotationally powered giant pulses (Lyutikov et al. 2016; Connor et al. 2016; Cordes & Wasserman 2016) are best guesses.

• ”The Repeater years”: from Spitler et al. (2016) to Apr 28 2020. FRBs must come from non-destructive sources. Rotationally powered giant pulses are excluded by energetics (Lyutikov 2017). Magnetars are best guess, but there are mild observational constraints (Lyutikov & Rafat 2019). Observations of consistent spectral drifts (CHIME/FRB Collaboration et al. 2019; Hessels et al. 2019) point to magnetospheres of NSs as loci of emission (Lyutikov 2002, 2020b).

• CHIME years (Boyle & Chime/Frb Collaboration 2018): 2018-

3. SGR 1935+2154 and constraints on local FRB properties

3.1. Properties of SGR 1935+2154

SGR 1935+2154 was discovered due to a weak $\sim 0.3$ s burst in 2014 by Swift (Stamatikos et al. 2014). Further analysis demonstrated that the source might be a magnetar (Lien et al. 2014). Pulsations with the period 3.245 s were recorded the same year by Chandra (Israel et al. 2014).

Dedicated Chandra and XMM-Newton observations, as well as analysis of archival data, allowed to measure precisely parameters of the magnetar Israel et al. (2016). X-ray luminosity in quiescent state is $\sim \text{few} \times 10^{34}$ erg s$^{-1}$, i.e. slightly above spindown luminosity $\dot{E}_{\text{rot}} = 1.7 \times 10^{34}$ erg s$^{-1}$. Spectrum can be fitted by a combination of the blackbody and power-law radiation. The source was also identified in pre-burst archive data of XMM-Newton with luminosity $\geq 10^{34}$ erg s$^{-1}$, i.e. with $L_x \approx \dot{E}_{\text{rot}}$, which put the source on the boundary between radio-silent and radio-loud magnetars (the former typically have $L_x > \dot{E}_{\text{rot}}$). Early attempts to detect radio emission from SGR 1935+2154 after 2014 outburst resulted just in upper limits $\sim 0.1$ mJy.

SGR 1935+2154 is associated with a shell-type supernova remnant G57.2+0.8. This allows to
determine the distance of 12. ± 1.5 kpc (Kothes et al. 2018). In addition, an age estimate ∼few tens of thousand years (with the more probable value 41 000 yrs) was obtained. These number a roughly compatible with the spin-down age ∼ 3.6 kyr. (It is tempting to speculate that the age determined via SNR studies is slightly larger than the spin-down age due to magnetic field emergence, see Bernal et al. (2013) and references therein.) A pulsar wind nebula is suspected due to diffuse emission detected in X-rays Israel et al. (2016).

With a period $P = 3.24$ seconds, and period derivative $\dot{P} = 1.4 \times 10^{-11}$ (Olausen & Kaspi 2014) the surface magnetic field $B_{NS}$ and the fields at the light cylinder $B_{LC}$ evaluate to

$$B_{NS} = 2.2 \times 10^{14} G$$

$$B_{LC} = 60 G$$

(1)

3.2. Radio burst from SGR 1935+2154: a weak FRB

Based on the data by STARE2 (fluence ∼MJy ms) and CHIME (duration about 40 ms, due to two 5 ms bursts and 30 ms interval between them) we obtain:

$$L_R = 0.66 \times 10^{37} \left( \frac{d}{12.5 \text{kpc}} \right)^2 \left( \frac{\nu}{1.4 \text{GHz}} \right) \left( \frac{\text{fluence}}{1 \text{MJy} \times \text{msec}} \right) \left( \frac{\text{duration}}{40 \text{msec}} \right)^{-1} \text{erg s}^{-1}.$$  

(2)

This estimate of intrinsic luminosity depends sensitively on the uncertain location of the source within the radio beam! Intrinsic luminosity could be higher!

Taken at face value, luminosity (2) is lower than typical intrinsic radio luminosities of FRBs, which are estimated at $\sim 10^{39} - 10^{42}$ erg s$^{-1}$ for isotropic emission. (If one uses the value of fluence reported by CHIME — few kJy×ms, — then the radio luminosity goes down by $\sim 3$ orders of magnitude.)

Thus, the intrinsic luminosity of FRB from SGR 1935+2154, Eq. (2), as well as the brightness temperature $T_b$, Eq. (4), are still short of the cosmological FRBs, that require e.g., peak luminosity above $10^{40}$ erg s$^{-1}$. Given the spread of FRBs’ intrinsic luminosities, it is reasonable to assume that the radio burst from SGR 1935+2154 represent a lower end of a broad distribution of FRBs’ power: “only some special types of magnetars can produce [cosmological] FRBs” (as argued by Lyutikov 2020b). (We also note that previous observations did not detect radio bursts from SGR 1935+2154 Younes et al. 2017, this further indicates that there is a range of luminosities of radio bursts). (We thank Jason Hessels for pointing these issues to us.)

Note, that recently numerous weak short radio bursts were detected from another galactic magnetar XTE J1810-197 (Maan et al. 2019). However, no accompanying high energy activity

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3We use this value in the paper, however, recently Zhou et al. (2020) estimate the distance as 6.6 ± 0.7 kpc, i.e. twice smaller.
was registered. These events had relatively low radio fluxes ($\lesssim 10$ Jy down to $\sim$mJy), so intrinsic luminosity is $\sim 10^{11}$ times lower than, for example, in bright bursts of FRBs 121102.

### 3.3. Emission radius of the radio burst

In this section we demonstrate that the parameters of SGR 1935+2154 are generally consistent with requirements to produce bright coherent FRB within the magnetar magnetosphere (Lyutikov & Rafat 2019).

GCN 27668 reported that during the active phase the persistent X-ray luminosity is $L_X \sim$ few $\times 10^{35}$ erg s$^{-1}$. This is larger than the spindown luminosity, placing SGR 1935+2154 among “classical magnetars”. What is even more exciting, the peak (isotropic equivalent) radio luminosity to (2) exceeds the spindown power. Most importantly, this radio dominance excludes rotationally-powered emission as argued by Lyutikov (2017).

Given the magnetic fields (1) the cyclotron frequency at the light cylinder is

$$\frac{\omega_{B,LC}}{2\pi} = 2 \times 10^8 \text{Hz}$$

Thus, the emitted radio waves' frequency, if FRBs originate within the magnetosphere, is typically below the cyclotron frequency. This is highly important for a consistent description of FRBs emission (Lyutikov & Rafat 2019). (Also, the cyclotron absorption, if any, is likely to be in the magnetosphere, not the wind. Luo & Melrose 2001)

The radiation energy density at the source and the observed brightness temperature evaluate to (we neglect for simplicity possible relativistic motion Lyutikov & Rafat 2019)

$$u_r = \frac{\nu F_{\nu} d^2}{c^3 \tau^2}$$

$$T_b = \frac{u_r}{2\pi k_B} \lambda^3 = 8 \times 10^{30} \text{K}$$

The equipartition magnetic field is

$$B_{eq} = \sqrt{8\pi u_r} = \sqrt{8\pi \left(\frac{\nu F_{\nu}}{c^3 \tau^2}\right)^{1/2} d} = 2 \times 10^6 \text{G}$$

The equipartition magnetic field is a lower estimate on the magnetic field in the emission region (Lyutikov et al. 2016). Given the surface magnetic field (1), this limits the emission radius to

$$\frac{r}{R_{NS}} \leq \left(\frac{B_{NS}}{B_{eq}}\right)^{1/3} = 300$$

Thus, emission is produced in the inner parts of the magnetar magnetosphere.
Laser intensity parameter $a$ (Akhiezer et al. 1975) evaluates to

$$a = \frac{eF_{\nu}^{1/2}d}{\sqrt{\pi}m_ec^{5/2}\sqrt{\nu_T}} = 5 \times 10^3$$

(7)

As discussed by Lyutikov (2017); Lyutikov & Rafat (2019); Lyutikov (2020a), such large intensity parameter requires large magnetic field: otherwise coherently emitting particles will have dominant “normal” losses (synchrotron and inverse Compton losses). In high magnetic field instead of large oscillations with momentum $p_{\perp} \sim am_ec$ coherently emitting particles experience mild $E \times B$ drift. This requires $\omega_B \geq \omega$; this condition is satisfied at radii (6).

### 3.4. Plasma parameters at the radio burst production cite

Magnetar magnetospheres are non-potential configurations (Lynden-Bell & Boily 1994; Thompson et al. 2002b), twisted by the Hall drift in the NS’s crust (Goldreich & Reisenegger 1992; Rheinhardt & Geppert 2002; Cumming et al. 2004; Reisenegger et al. 2007; Lyutikov 2013; Wood et al. 2014; Gourgouliatos et al. 2015). Current-carrying magnetospheric charges moving with Lorentz factor $\Gamma$ have a rest-frame density of

$$n' = \Delta\phi \frac{B}{2m_e r \gamma_s}$$

(8)

where $\Delta\phi$ is a typical twist angle (Thompson et al. 2002b), and $n'$ is plasma density in its center-of-momentum frame.

Radiative efficiency less than unity (radiation energy density less than plasma energy density) then requires (Lyutikov & Rafat 2019)

$$\gamma\gamma_s^3 \geq \frac{e\nu^3 r k_B T}{m_e c^3 B \Delta\phi} = 6 \times 10^{13} \nu_{GHz}^3 \frac{1}{\Delta\phi} \left( \frac{r}{R_{LC}} \right)^4$$

(9)

where $\gamma$ is the spread of the Lorentz factors in the center-of-momentum frame and $\gamma_s$ is the bulk streaming Lorentz factor. The extremely high brightness temperatures in FRBs likely involves relativistic plasmas, $\gamma, \gamma_s \gg 1$. (Lyutikov & Rafat (2019) also included effects of radiation anisotropy; this decreases the demands on plasma energy content.)

Near the neutron star surface the condition (9) evaluates to

$$\gamma\gamma_s^3 \geq 10^{-3} \nu_{GHz}^3 \frac{1}{\Delta\phi}$$

(10)

This can be easily satisfied even for very mild twist $\Delta\phi \leq 1$.

We conclude that the inner part of the magnetosphere of SGR 1935+2154, the magnetic field and expected plasma density, satisfies the physical requirements to produce high brightness coherent emission.
4. Solar physics of magnetars

Lyutikov (2006b) discussed similarities between Solar flares and magnetar phenomenology, the "Solar physics of magnetars". Detecting of radio bursts contemporaneous with high energy bursts further strengthens this analogy.

Light curves and radio-X-ray relative timing may also hold clues to interpretation of flares. The first radio pulse is delayed by 100-200 ms relative to the X-ray emission onset in the Konus-Wind softest energy band (GCN 27669, ATel 13688). This behavior is qualitatively similar to the solar flares, where soft X-ray emission starts to rise before the prompt flare (e.g., Fig. 2 in Benz 2008). In addition, in Solar flares soft X-rays continue longer than the prompt non-thermal X-rays and microwaves spikes ("Neupert effect" Neupert 1968). In case of the Sun the interpretation is that the soft X-rays originate from plasma heated by the primary flare’s electrons. In the case of magnetars we expect that reconnection events lead to abundant pair production, and "pollution" of the acceleration region, as we discuss next.

According to GCN 27668, Integral detected a peak flux of \( \sim 10^{-6} \) erg cm\(^{-2}\) s\(^{-1}\) (which can be slightly underestimated), this corresponds to peak luminosity \( L_\gamma = 9 \times 10^{39} \) erg \(^{-1}\). For a duration of \( \tau_\gamma \sim 10 \) msec the compactness parameter evaluates to

\[
l_c = \frac{\sigma T L_\gamma}{m_e c^4 \tau_\gamma} \approx 10^3
\]

Thus, we expect abundant pair production following the gamma-ray flare.

We hypothesize that the radio emission is generated during the initial stage of magnetospheric reconnection, while the magnetosphere is still relatively clean of the pair loading. The giant \( \gamma \)-ray flare from the magnetar SGR 1806 - 20 had a rise time of only 200 micro-seconds (Palmer et al. 2005). (X-ray bursts may actually suppress radio emission, e.g., in the case of mixed magnetar/radio pulsar PSR J1119-6127, Archibald et al. 2017).

We favor the "Solar flare" paradigm of magnetar flares driven by plastic deformations of the crust (Levin & Lyutikov 2012; Lyutikov 2015), as opposed to "starquakes" model of (Thompson & Duncan 1993). Levin & Lyutikov (2012) demonstrated that magnetically-induced cracking is not possible: burst and flares are more naturally produced as magnetospheric events, analogous to Solar flares (Lyutikov 2015).

The total energy budget of the burst, \( \sim 10^{39} \) erg, can be easily accomodated. For surface magnetic field (1) the required volume of dissipated magnetic energy corresponds to only few tens of meters cubed, much smaller than the size of the neutron star. The magnetic energy budget in magnetars could in fact be higher than the one estimated from the surface fields due to the large required toroidal fields in the crust (e.g Flowers & Ruderman 1977; Braithwaite & Nordlund 2006; Gourgouliatos et al. 2013)

We also note that the high energy and radio burst from SGR 1935+2154 lies not far from
Fig. 1.— X-ray and centimeter radio luminosities of stellar flares (Benz & Güdel 2010) and radio (STARE2, ATel 13681) and X-ray (Konus-Wind, ATel 13688) flares from SGR 1935+2154. (Figure to be updated with original data once they become available after the end of the lockdown).

the so-called Güdel-Benz relationship, which relates the thermalized X-ray luminosity generated by magnetic reconnection in stellar flares to the nonthermal, incoherent, gyrosynchrotron radio emission that results from particle acceleration Benz & Güdel (for a review 2010, also see a comment after Eq. (2) about the uncertainty in radio luminosity of SGR 1935+2154). This relationship is given by \( \frac{L_X}{\tilde{L}_R} \sim 10^{15.5 \pm 0.5} \) [Hz], where \( L_X \) is the X-ray luminosity and \( \tilde{L}_R \) is the radio flux per unit frequency. Using peak X-ray flux (ATel 13688) of \( F_X = (9 \pm 2) \times 10^{-6} \) erg cm\(^{-2}\) s\(^{-1}\) (in the 20 - 200 keV energy range) the ratio estimates to 6 \( \times 10^{13} \): not too far off!

Güdel-Benz correlation is usually interpreted that first electrons are accelerated to non-thermal velocities and emit radio, then these particles are thermalized and emit thermal X-rays. The magnetar SGR 1935+2154 adds another point, with an important caveat that the radio emission in this case is coherent. (Interestingly, it also lies off to the “expected” side from the lower energetics
fit: the radio is too bright, as expected for coherent emission.) Though the microphysics of this relation is far from clear, is it at least consistent with the concept that accelerating mechanism puts first energy into nonthermal particles that produce radio, and then that energy is thermalized, producing X-rays.

Solar X-ray flares show a power law distribution of energies, extending over many orders of magnitude (Benz & Güdel 2010). The value of the power law index and the origin of this distribution is not clear: a self-organized criticality (sand pile model) is one possible explanation. Qualitatively, magnetic configurations are nonlinear systems that show a “threshold”-type behavior: slow evolution below threshold gives rise to exponential growth after the instability threshold is crossed. In application to FRBs, we similarly expect a broad range of bursts’ energetics.

Another important point is the similarity of the polarization properties of the magnetar burst (ATel 13699) and of original repeaters FRB 121102 and FRB 180916.J0158+65 (Michilli et al. 2018; CHIME/FRB Collaboration et al. 2019). They all show \( \sim 100\% \), linear polarization, negligible circular polarization and a consistently flat PA. This consistent polarization patterns, as well as consistently drifting spectral features imply a kind of “confining structure”: the magnetospheric magnetic fields. These consistent features also imply that the duration of the pulses are intrinsic, as opposed to being due to a beam that is longer lived and sweeps past the line of sight. (We thank Jason Hessels for stressing this similarity.)

The origin of the coherent emission of FRBs remains a mystery (as well as that of regular pulsars). As discussed by Lyutikov et al. (2016) we can identify three types/mechanisms of radio emission in neutron stars: (i) normal pulses, exemplified by Crab precursor, Moffett & Hankins (1996); (ii) giant pulses, exemplified by Crab Main Pulse and Interpulse (Lundgren et al. 1995; Popov et al. 2006; Lyubarsky 2019; Philippov et al. 2019); (iii) radio emission from magnetars (coming from the region of close field lines, e.g., Lyutikov (2002); Eichler et al. (2002); Camilo et al. (2006). FRBs should be of type-iii radio emission.

The lack of understanding of mechanisms of radio emission from normal pulsar is a major impediment to the future progress (e.g., Melrose 1995; Lyutikov et al. 1999; Melrose & Gedalin 1999; Beskin et al. 2015). Note, that coherent curvature emission by bunches, popular in the early years of pulsar research (Goldreich & Keeley 1971; Cheng & Ruderman 1977), is not considered a viable emission mechanism (Benford & Buschauer 1977; Asseo et al. 1990; Melrose 1992; Melrose & Gedalin 1999). In addition, in case of repeating FRBs the absence of periodicity excludes narrow region of open field lines for the production of coherent emission. In a magnetar paradigm reconnection events occurring in broad regions of the magnetosphere may hide the rotational period.

5. Discussion and expectation

Detection of MJy radio burst from a Galactic magnetar and many similarities to FRBs points to magnetically powered “classical magnetars” as the loci of FRBs. Temporal coincidence between
radio and high energy emission, down to milliseconds, further limits the FRB loci to the magnetospheres of magnetars (as opposed to winds).

Radio emission from reconnection events in magnetars’ magnetospheres was previously predicted/discussed by Lyutikov (2002, 2003, 2006a, 2015). In particular, drawing on analogies with solar flares, Lyutikov (2002) predicted that coherent radio emission may be emitted in SGRs during X-ray bursts. Thus, these event are reconnection-driven emission processes occurring in magnetars’ magnetospheres. In addition, Lyutikov (2002) argued that emission should have downward drifting central frequency in analogy with solar type III radio bursts. Though such drifts have not yet been seen in magnetars, they were indeed detected in FRBs (Hessels et al. 2019; The CHIME/FRB Collaboration et al. 2019a,b; Josephy et al. 2019; Lyutikov 2020b). Observations of such drifts in magnetar bursts would further strengthen FRB-magnetar connection.

In this paper we demonstrate that extremely demanding conditions on plasma parameters at the sources of FRBs, discussed previously by Lyutikov & Rafat (2019), can be easily accommodated in the case of SGR 1935+2154, with no extreme assumption about the expected local plasma parameters. (This is due to the identification of the source, giving us estimates of distance, period and period derivative.) On the one hand, a particular radio burst from SGR 1935+2154 is at least \( \sim 100 \) times less powerful than the weakest FRB detected. On the other hand, magnetar SGR 1935+2154 is not a particularly special magnetar in any respect. There is a “room” in parameter space to produce brighter radio bursts.

Perhaps the first FRB-magnetar connection was discussed by Popov & Postnov (2007) who suggested that FRBs can be due to hyperflares on magnetars, whose X/\( \gamma \)-rays emission is undetectable from distances \( \geq 100 \) Mpc. It was shown that from the point of view of total energy budget, rate, timescale, and lack of counterparts properties of energetic flares of extragalactic magnetars are consistent with the hypothesis that they produce millisecond radio flares. The mechanism of radio emission production was not specified, but the authors used the model by Lyutikov (2002) to obtain basic numbers and to speculate about radio flares of different energy related to correspondingly different X/\( \gamma \)-ray bursts. When the paper by Thornton et al. (2013) appeared, Popov & Postnov (2013) noticed that the magnetar hypothesis fits well new data, too.

In terms of astronomical locations, the picture is not clear: the two well-localized repeaters (FRB 121102 and FRB 180916.J0158+65) are both found coincident with star-forming regions (Bassa et al. 2017; Marcote et al. 2020). This is consistent with magnetar origin. At the same time, the (apparent) non-repeaters are not obviously associated with star formation (Bannister et al. 2019). One possibility is that the non repeaters are much older NSs that only very occasionally produce a bright burst (we thank Jason Hessels for pointing this to us).

Looking forward, we expect that more pulsar-like phenomenology to be discovered in FRBs. Though the energy sources in pulsars and magnetars are different (rotational energy versus the magnetic field), the overall dominating magnetic field is expected to impose many similar observational effects. The most obvious is the periodicity, reflecting the rotational period of the neutron
star. Another prediction is the polarization swings through the pulse (rotating vector model is a cornerstone of pulsar phenomenology Radhakrishnan & Cooke 1969). Polarization swings are expected in case of emission originating on magnetars' close field lines, but shorter rotational period NSs produce large PA swings (Lyutikov 2020b). PA swings were not seen in this particular case (ATel 13699), presumably due to the fairly long period of a neutron star; still a high degree of linear polarization is consistent with highly structured magnetars' magnetosphere. Curiously, microseconds-long giant pulses from Crab pulsar, with approximately similar relative pulse duration, do sometimes show flat polarization angle. Giant pulses are also likely to be generated in reconnection events, though outside the light cylinder (Hankins et al. 2016; Cerutti et al. 2016; Cerutti & Beloborodov 2017; Philippov et al. 2019). We also expect detection of narrow spectral features and frequency drifts in magnetar radio bursts, akin to the ones seen in FRBs. This will further solidify the association.

Finally, the identification of FRBs with magnetars implies that we are not likely to detect cosmological FRBs by all-sky X-ray/gamma-ray monitors. As discussed by Lyutikov & Lorimer (2016), given the magnetars’ X-ray flares maximal radio power of $\sim 10^{47}$ erg sec$^{-1}$ (Palmer et al. 2005), they can be detected only to $\sim 100$ Mpc. On other other hand, sensitivity of imaging high energy telescopes may allow observations of contemporaneous FRB/gamma-ray flares in the previously identified repeaters out to $\sim$ Gpc (see also Scholz et al. 2017, 2020; Cunningham et al. 2019). Also, simultaneous detection in optical may be possible (e.g., by "shadowing" of CHIME field by an optical telescope, Lyutikov & Lorimer 2016).

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