Detectability of radio afterglows from Fast Radio Bursts produced by Binary Neutron Star Mergers

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Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT
Binary neutron star (BNS) mergers are one of the proposed origins for both repeating and non-repeating fast radio bursts (FRBs), which associates FRBs with gravitational waves and short gamma-ray bursts (GRBs). In this work, we explore detectability of radio counterparts to an FRB by calculating the radio afterglow flux powered by the two components: a relativistic jet and a slower isotropic ejecta from a BNS merger. Detection probability of a radio afterglow for a FRB is calculated as a function of the source redshift, observing time, and flux sensitivity, assuming that FRBs are not strongly beamed. The model parameter distributions inferred from short GRB afterglows are adopted. We find that the detection probability for an FRB at \( z = 0.5 \) is 3.7 and 4.1 % for the jet and isotropic components, respectively, when observed at the timing of their peak flux (\( \sim 10 \) days and 1 year) with a typical sensitivity of \( 10^{\mu} \) Jy. The probability increases to 10 and 14 %, respectively, with \( \sim 1 \mu \) Jy sensitivity achievable with future facilities (e.g. SKA). In particular for the repeating FRB 180916.J0158+65, we find a high chance of detection (60% at \( 10^{\mu} \) Jy sensitivity) for the isotropic component that would peak around \( \sim 10 \) years after the merger, as a natural consequence of its close distance (\( z = 0.03 \)). Therefore a long term radio monitoring of persistent radio emission for this object is important. The detection probability is similar for the jet component, though the peak time (\( \sim 200 \) days) has likely already passed for this FRB.

Key words: gravitational waves — stars: neutron — binaries: close —

1 INTRODUCTION
Fast radio bursts (FRBs) are radio transients with an intrinsic pulse width of milliseconds, whose origin is still enigmatic (Thornton et al. 2013). Nearly 100 FRBs have been discovered (Petroff et al. 2016)1 since the first event archived in 2001 and reported in 2007 (Lorimer et al. 2007), with an all sky rate \( \sim 10^3 - \) \( 10^4 \) sky\(^{-1}\) day\(^{-1}\) above a 1 Jy ms fluence threshold (Keane & Petroff 2015; Lu & Piro 2019). Their large dispersion measures (the integrated column density of free electrons along the line of sight) exceeding the contribution by electrons in the Milky Way Galaxy, as well as the direct localization of host galaxies of some FRBs, point to an extragalactic origin and implies source redshift in the range of \( z = 0.1-1 \) (Chatterjee et al. 2017; Marcote et al. 2017; Tendulkar et al. 2017; Bannister et al. 2019; Prochaska et al. 2019; Ravi et al. 2019; Cordes & Chatterjee 2019; CHIME/FRB Collaboration et al. 2019; Lu & Piro 2019). While some of the FRBs are found to be repeating sources (Spitler et al. 2016; CHIME/FRB et al. 2019; CHIME/FRB Collaboration et al. 2019), most seem to appear only once despite the intensive searches for possible repeating signals (Lorimer et al. 2007; Petroff et al. 2015; Shannon et al. 2018). The distribution of intrinsic pulse time width is different for repeating and non-repeating FRBs, as observed by CHIME, which implies different origins of these two populations (CHIME/FRB Collaboration et al. 2019).

The high power and short timescale of FRBs naturally associate them with compact stars (see reviews by Cordes & Chatterjee 2019; Platts et al. 2019), especially neutron stars because of their enormous gravitational and electromagnetic energies and short characteristic time scales of \( O(GM/c^3) \sim 10\mu s \). One scenario is that a non-repeating FRB is produced at the time of merger of a binary neutron star (BNS) (Totani 2013; Zhang 2014; Wang et al. 2016; Yamasaki et al. 2018), while repeating FRBs may also be powered by the surviving remnant from the merger (Yamasaki et al. 2018; Margalit et al. 2019). The BNS merger scenario is particularly interesting because of the potential

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The possible relation between FRBs and BNS mergers leads to potential multi-wavelength electromagnetic counterparts including short gamma-ray burst afterglow and r-process kilonovae like those observed in the BNS merger event GW170817 (see Abbott et al. 2017a,b, and references therein). Such a hypothesis has been tested by deep targeted search for FRBs from GRB remnants (Madison et al. 2019; Men et al. 2019) and optical follow-up of FRBs (Ninno et al. 2014, 2018; Tomimaga et al. 2018), but no significant candidate has been identified. Identification of any electromagnetic counterpart to an FRB will not only help pinpoint its host galaxy, but also provide crucial information on the progenitor system and ambient environment.

Throughout this paper we consider BNS mergers as the progenitor model for (both repeating and non-repeating) FRBs, and focus on the detectability of radio afterglows lasting for years by a relativistic outflow interacting with ambient matter (Nakar & Piran 2011; Troja et al. 2019; Hajela et al. 2019). Like what we observed in GW170817, a BNS merger produces a relativistic structured jet that contains an energetic core and exponentially faints outward, and also produces a quasi-isotropic neutron-rich ejecta that powers a kilonova (e.g. Troja et al. 2019; Villar et al. 2017, and reference therein). Both a jet and an isotropic ejecta will result in observable afterglow with different observable brightness and timescales, and we discuss their detectability by radio observations in order to test the BNS merger model of FRBs.

For calculation of radio afterglows from BNS mergers, we use the model developed by our previous work (Lin et al. 2019). A unique point of this model is treating the efficiency of electron acceleration and the minimum electron energy as independent parameters, while other previous models made an oversimplified assumption that all electrons in the shock is accelerated as nonthermal particles. As a result of one more degree of freedom, we found a quantitatively different fit to the observed light curve of GW170817.

The paper is organized as follows: in Section 2, we describe the models of outflow dynamics and afterglow emission. In Section 3, we present radio afterglow light curve calculation, Monte Carlo simulation of flux distribution, and determine detection probability as function of given source redshift and detector sensitivity. The discussion and conclusion are given in the Section 4 and 5.

Table 1. Median and 1σ scatter of Gaussian fit to the parameter cumulative distributions by short GRB afterglow observation (Fong et al. 2015).

| Parameters | Median | Standard Deviation |
|------------|--------|--------------------|
| log($E_{k,ine}$ [erg]) | 51.2 | 0.83 |
| log($n$ [cm$^{-3}$]) | -1.57 | 1.63 |
| $\theta_j$ [deg] | 5.8 | 1.2 |
| $p$ | 2.39 | 0.23 |

Figure 1. Radio (1.4 GHz) afterglow light curves of structured jet viewed in various angles (blue) and isotropic ejecta (orange) from a source at $z = 0.5$. The solid lines account for the typical ambient density in a star forming galaxy (1 cm$^{-3}$) while dotted lines for an old elliptical galaxy (10$^{-3}$ cm$^{-3}$).
function of comoving photon frequency $\nu$ and shock radius $R$ using the public Python package naima (Zabalza 2015). The effect of synchrotron self absorption is ignored since it does not affect our result significantly.

Finally, the energy flux received by a distant observer is obtained by integrating the Doppler boost of $P(\nu, R)/(4\pi D_L^2)$ over the photon equal time arrival surface, which can be solved from $\beta(R)$ in all directions (see also Granot et al. 1999), given the following observer parameters: observed photon frequency $\nu_{\text{obs}}$, observed time $t_{\text{obs}}$, viewing angle $\theta_{\text{obs}}$, and luminosity distance $D_L$.

3 RESULT

3.1 Radio afterglow light curve

Radio (1.4 GHz) afterglow light curves from a source located at $z = 0.5$, the median redshift of detected FRBs (e.g. Petroff et al. 2016), are shown in Fig.1 for illustration. The parameters for jet/ejecta components are chosen as follows: $E_{k,\text{iso}} = 10^{51}$ erg, $\Gamma_0 = 100$, $\theta_j = 6^\circ$, and viewing angles ranging from 0 to 0.5 for jet; $E_{k,\text{iso}} = 10^{51}$ erg, $\Gamma_0 = 1.05$, $\alpha \rightarrow \infty$ (i.e. single velocity) for ejecta. The common parameters are $\epsilon_e = 0.1$, $\epsilon_B = 0.01$, $p = 2.2$, $f = 1$, and the typical ISM densities in a star forming galaxy ($10^{-3}$ cm$^{-3}$) and an old elliptical galaxy ($10^{-9}$ cm$^{-3}$), respectively (Wiggins et al. 2018).

Note that while the jet afterglow seems to be brighter than the ejecta afterglow in Fig.1, viewing angles in the presented range only constitute 13% of the whole population assuming random binary orientation. For the median value ($\langle \theta_{\text{obs}} \rangle = 60^\circ$), jet produces comparable afterglow flux to ejecta, which results in the comparable detection probability (but different peak time) shown in Fig.2 and 3.

3.2 Detection probability from simulated events

Here we present estimate of radio afterglow detection probability, assuming the model parameter distributions as follows. For the jet component, we assume the orientation of the BNS system to be uniform spherical distribution, i.e. we set $\theta_j < 90^\circ$ and 0 otherwise. The initial Lorentz factor $\Gamma_0 = 100$ is fixed. We adopt the Gaussian fits (Table.1) to the cumulative distributions of isotropic-equivalent on-axis energy $E_{k,\text{iso}}^\text{O}$, ambient density $n$, opening angles $\theta_j$ and electron index $p$ inferred from short GRB afterglow observations (Fong et al. 2015, F15), with fixed values of $\epsilon_e = 0.1$, $\epsilon_B = 0.01$, $f = 1$ and a lower bound of $n_{\text{min}} = 10^{-4}$ cm$^{-3}$ for the $n$ distribution imposed by F15. The distribution of $\theta_j$ is estimated using only GRBs showing jet breaks in their afterglows.

For the isotropic ejecta component, the same distributions of $n$ and $p$ are used, but $E_{k,\text{iso}} = 10^{51}$ erg and $\Gamma_0 = 1.05$ are fixed because no observational constraint is available for its scatter. We assume $\alpha \rightarrow \infty$ (i.e. single velocity structure) for simplicity, also considering the observational constraint $\alpha > 6$ suggested from late time radio monitoring of GW170817 (Hajela et al. 2019).

Producing many model parameter sets by the Monte-Carlo method, we calculated radio light curves for each model set, and determined the detection probability as a function of a given detection threshold $F_{\text{lim}}$, a source redshift $z$, and the observation time $t_{\text{obs}}$. The result is shown
Figure 3. The maximum detection probability (upper) and the corresponding best observation time (lower) as a function of redshift and detector sensitivity. FRBs with reported upper limits on a persistent radio emission listed in Table 2 are shown by plus marks.

4 DISCUSSION

4.1 Detection prospects

At the typical sensitivity of current radio telescopes (10–100 µJy), the detection probability is estimated to lie between 1–10% for a source located at $z < 1$ (which includes the majority of the present FRB sample), and increase to >10% at $z < 0.1$. At 1 µJy sensitivity, which is the designed level of SKA, all FRBs with $z < 1$ will have >10% detection prospects. Due to the comparable radio flux density levels produced by the jet (with median value of viewing angle $\langle \theta_{\text{obs}} \rangle = 60^\circ$) and isotropic afterglow components, the maximum detection probabilities at the best observing time have similar appearance for the two components on the redshift-sensitivity plane (Fig. 3). However, the peak time is much
earlier for jet afterglow (~10 days after the merger) due to the relativistic velocity of jet, compared with the mildly-relativistic isotropic ejecta (~1 year after the merger).

Note that Fig. 3 shows a tendency of later peak time \( t_p \) towards closer distance and higher sensitivity. The key to interpret this result is the scaling relation of afterglow peak flux and peak time: \( F_p \propto E_{\text{kin,iso}}^{0.5p+1}/4, \quad t_p \propto (E_{\text{kin,iso}}/n)^{1/3}. \) If the scatter in \( E_{\text{kin,iso}} \) is negligible, the scatter in ambient density \( n \) leads to a negative correlation \( F_p \propto t_p^{-3p+3}/4, \) i.e. fainter event with later peak time. This negative correlation remains true as long as \( E_{\text{kin,iso}} \) is less scattered compared with \( n \), which is the case for short GRBs (Table 1), though the correlation is weaker due to the finite scatter of \( E_{\text{kin,iso}} \). Consequently, a higher sensitivity or a closer source will allow much fainter detections, which eventually leads to the tendency of later peak time.

### 4.2 Consistency with radio afterglow limits on FRBs

We discuss whether or not the available limits on persistent radio emission imposed on some FRBs by follow-up observations is consistent with our calculated detection probability. From Table 2, we found that the detection probabilities for most FRBs are typically in the range of 1–10%. Considering that the total number of the available sample is less than 10 FRBs, the non-detection of any associated radio afterglow does not strongly constrain the BNS progenitor model.

Repeating FRB 180916.J0158+65 is the only exceptions with a promising detection prospect (~60% at 20 \( \mu \)Jy sensitivity) for the isotropic component that peaks around ~10 years after the merger, as a natural consequence of its close distance (\( z \approx 0.03 \)). Yet the probability does not go up to 100% mainly because of the low ambient densities that may appear in the adopted parameter distribution. We further note that the repeating FRB activity would start 1–10 years after a BNS merger Yamasaki et al. (2018). Therefore there is a reasonable chance to detect a radio afterglow for this source in the near future, though no detection does not give a strong constraint.

The ambient density distribution adopted in this work from F15 is widely spread from \( 10^{-4} \) to \( 10 \, \text{cm}^{-3} \). However, some FRBs listed in Table 2 are well localized to a type-specified host galaxy. Therefore, the detection probability is underestimated if the source is localized in high density environment like star-forming region (e.g. FRB 180916.J0158+65), and overestimated if localized in a more diffuse environment like an early-type galaxy or outskirt regions (e.g. FRB 180924, 190523).

### 4.3 Caveats on the jet opening angle

The distribution of jet opening angle \( \theta_j \) assumed in this work significantly affects the detection probability as it scales with \( \theta_j^2 \). We note one important caveat that while we assumed the same parameter distributions for short GRBs and FRB afterglows in the BNS merger progenitor model, the parameter space in which an FRB is produced may not coincide with...
that for successful GRB jet formation. One such scenario is that FRBs may appear in a BNS merger with a “choked” or failed jet in the parameter space of smaller $(E_{\text{iso}})_{\text{jet}}$ and larger $\theta_j$, e.g. $(E_{\text{iso}})_{\text{jet}} < 0.05(E_{\text{iso}})_{\text{iso}} \theta_j^2$ (Duffell et al. 2018), which may produce a bias against afterglow detections at larger viewing angle $(\lesssim 23^\circ)$. However, the resulting detection probability does not necessarily increase because the expected flux is fainter at a larger viewing angle.

Another caveat is that we have used the $\theta_j$ distribution of F15 based on 4 short GRBs with jet break measurements, which is narrowly peaked at $6^\circ$ with a $1\sigma$ scatter of $1^\circ$. F15 also provided another distribution by including 7 more samples with lower bounds on $\theta_j$ and assuming equal weighting over all 11 events, which extends the cumulative distribution almost linearly to an ad hoc maximum angle $(30^\circ, 90^\circ)$. Considering the uncertainty in the treatment of these additional events, and the fact that the value of narrow $\theta_j$ distribution is well consistent with the jet width ($\theta_j \sim 5^\circ$) seen in GW170817 (Troja et al. 2019; Hajela et al. 2019), we only adopt the narrow distribution model in this work as a conservative estimate for the detection probability (since it scales with $\theta_j^2$).

The final remark is that $\theta_j$ in F15 are measured as the jet edge of a top-hat jet, different from the definition of jet width in our Gaussian jet model. For a same jet break time observed in a short GRB afterglow, the Gaussian jet model will measure a slightly smaller $\theta_j$ (roughly by a factor of 0.7). However, the resulting difference of detection probability is at most a factor of 2, and hence we ignored it.

5 CONCLUSION

In this work we examined the prospects of detecting radio afterglows of FRBs, in the scenario that FRBs are produced by BNS mergers. We considered the two components of outflow: a relativistic jet and a mildly relativistic and isotropic ejecta. Detection probabilities were calculated as a function of sensitivity, source redshift and an observation time (Fig.2), assuming random viewing angles from the jet axis (i.e. assuming that FRBs are not strongly beamed) and adopting the model parameter distributions inferred from short GRB observations.

As a result, we found that the detection probability from FRBs at $z < 1$ is between 1–10% for the typical sensitivity ($10–100 \mu Jy$) of current radio telescope, which enhances to $>10\%$ if a $1\mu Jy$ sensitivity can be achieved by future facilities (e.g. SKA). The expected flux peaks typically at ~10 days for a jet afterglow and ~1 year for an isotropic afterglow. We also found a tendency of later peak time towards closer source and higher sensitivity, which can be attributed to the contribution from low luminosity events whose afterglows peak at a later time (Fig.3).

For individual FRBs with reported upper limits on a persistent radio flux, we listed their maximum detection probabilities for the two components at the best observation time in Table 2. Probability is less than 10% for most of these FRBs, and hence no detection does not give a strong constraint on the BNS merger scenario of FRBs. However, a future larger sample would give a meaningful constraint or lead to a detection of a radio afterglow. In particular for the repeating FRB 180916.J0158+65, we found a 60% chance of detection for the isotropic component whose flux peaks at about 10 years after the merger and remains detectable for a few decades, as a natural consequence of its close distance ($z = 0.03$). The time scale of 10 yrs is also comparable to the lifetime of repeating FRBs formed by a BNS merger. Though the detection probability is not close to 100% because of the distribution of model parameters, a long-term radio monitoring of this object is thus interesting.

ACKNOWLEDGEMENTS

HL was supported by the Japanese Government (MEXT) Scholarship and the JSPS Research Fellowships for Young Scientists. TT was supported by the JSPS/MEXT KAKENHI Grant Numbers 18K03692 and 17H06362.

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