Cosmological Fast Radio Bursts from Binary Neutron Star Mergers

Tomonori TOTANI

Department of Astronomy, School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033
Research Center for the Early Universe, School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033

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Abstract

Fast radio bursts (FRBs) at cosmological distances have recently been discovered, whose duration is about milliseconds. We argue that the observed short duration is difficult to explain by giant flares of soft gamma-ray repeaters, though their event rate and energetics are consistent with FRBs. Here, we discuss binary neutron star (NS–NS) mergers as a possible origin of FRBs. The FRB rate is within the plausible range of the NS–NS merger rate and its cosmological evolution, while a large fraction of the NS–NS mergers must produce observable FRBs. A likely radiation mechanism is coherent radio emission, like radio pulsars, by magnetic braking when magnetic fields of neutron stars are synchronized to binary rotation at the time of coalescence. Magnetic fields of the standard strength (\(\sim 10^{12}–13\) G) can explain the observed FRB fluxes, if the conversion efficiency from magnetic braking energy loss to radio emission is similar to that of isolated radio pulsars. Corresponding gamma-ray emission is difficult to detect by current or past gamma-ray burst satellites. Since FRBs tell us the exact time of mergers, a correlated search would significantly improve the effective sensitivity of gravitational wave detectors.

Key words: gravitational waves — radio continuum: general — stars: binaries: general — stars: neutron

1. Introduction

Thornton et al. (2013) reported the discovery of four enigmatic radio transients emitting Jansky-level flux during a few milliseconds, called fast radio bursts (FRBs) [see also Lorimer et al. (2007) and Keane et al. (2012) for earlier events of possibly the same population]. No repeated events were found, implying a cataclysmic nature. The dispersion measure and the scattering signature seen in the exponential tail of their light curves indicate that they are located at cosmological distances of redshift \(z \sim 0.5–1\). No counterparts were found at other wavelengths, and their origin is an intriguing mystery.

The short duration of \(\lesssim\) a few milliseconds would place a strong constraint on possible theoretical scenarios. Giant flares of soft gamma-ray repeaters (SGRs) are suggested to be a promising candidate by Lyutikov (2007), and Thornton et al. (2013), because the event rate is consistent with that of FRBs (Ofek et al. 2007), and sufficient total energy to explain the FRB radio flux (Hurley et al. 2005; Palmer et al. 2005; Terasawa et al. 2005). However, radio emission only within a millisecond scale duration is not naturally expected, though the dynamical time of a neutron star is about 1 ms. Typical rotation periods of SGRs are much longer (\(\gtrsim 1\) s), and a continued energy production at a giant flare would result in a longer radio emission than the dynamical time. Indeed, an unsaturated gamma-ray light curve of the 2005 giant flare of SGR 1806–20 shows a peak width of \(\sim 100\) ms, and subsequent modulation of the flux, indicating repeated energy injections on a time scale longer than 100 ms (Terasawa et al. 2005).

Other proposed scenarios for FRBs include the interaction of supernova shock and the neutron star magnetosphere (Egorov & Postnov 2009), annihiating black holes (Keane et al. 2012), collapses of supermassive rotating neutron stars (Falcke & Rezzolla 2013), and binary white-dwarf mergers (Kashiyama et al. 2013). In this letter we discuss whether binary neutron-star (NS–NS) mergers can explain the new results about FRBs, with a different picture than those adopted in previous studies about coherent radio emission from NS–NS mergers (Lipunov & Panchenko 1996; Hansen & Lyutikov 2001; Pshirkov & Postnov 2010; Lyutikov 2013).

2. Short-Duration Radio Emission from Binary Neutron Star Mergers

Electromagnetic (EM) wave signatures from NS–NS mergers have been widely investigated in the literature (e.g., Metzger & Berger 2012). Two popularly discussed emission mechanisms, i.e., the radioactivity of ejected material (Li & Paczyński 1998; Metzger et al. 2010; Roberts et al. 2011) and afterglows by energetic outflow interacting with the surrounding medium (Nakar & Piran 2011; Shibata et al. 2011; Piran et al. 2013), predict much longer time scales than milliseconds, and hence they are not relevant to FRBs. Rather, coherent radio emission from the neutron-star magnetosphere, like isolated radio pulsars, seems more plausible. Hansen and Lyutikov (2001) and Lyutikov (2013) (see also Lipunov & Panchenko 1996) considered pre-merger coheret emission from the interacting magnetosphere of a binary consisting of a recycled, weak magnetic field neutron star and a slowly rotating, strong field one, before their rotations are synchronized to the binary period. The radio flux predicted by Hansen and Lyutikov (2001) is much lower than those of FRBs, even if a very strong magnetic field (\(10^{15}\) G) is assumed. The flux estimated by Lyutikov (2013) is closer to the FRB flux, but it seems difficult to reconcile the predicted time evolution, \(\alpha (-\tau)^{-1/4}\), with the observed short duration, where \(\tau\) is the time before a merger whose minimum is \(\sim\) milliseconds.

Theoretically, it is expected that the rotations of neutron
stars are not tidally locked to the binary period until the last stage of merger when tidal disruption starts (Bildsten & Cutler 1992). Therefore, strong coherent emission by the rotation of individual neutron stars in a binary is not expected during gravitational inspiral. However, at some point in the last stage of a merger, their magnetic field configuration should be synchronized with the binary rotation, and coherent radio emission is expected by magnetic braking of a misaligned rotating magnetic dipole, or plasma effect in the magnetosphere, in a similar way to isolated radio pulsars. If synchronization occurs before a completely merged object forms, the radiation would come from the original magnetic dipole of a neutron star. Instead, the magnetic field of a merged object may be responsible for the radio emission, and in this case the magnetic field strength may be amplified by differential rotation (Pshirkov & Postnov 2010; Shibata et al. 2011).

Because of the strong dependence of the magnetic-breaking energy-loss rate on the rotation period \( \dot{E} \propto P^{-4} \), the luminosity should sharply increase with the synchronization of magnetic fields, and such coherent emission will continue until the merged neutron stars form a black hole (BH). Thus, this radiation mechanism seems favorable to explain the millisecond scale duration of FRBs. The expected energy-loss rate by magnetic braking can be estimated from the standard magnetic dipole radiation formula, using the typical magnetic field strength and radius of a neutron star, but with the binary orbital period at the time of coalescence, i.e., about milliseconds:

\[
\dot{E} = -6.2 \times 10^{45} \left( \frac{B}{10^{12.5} \text{ G}} \right)^2 \left( \frac{R}{10 \text{ km}} \right)^6 \left( \frac{P}{0.5 \text{ ms}} \right)^{-4} \text{ erg s}^{-1}.
\]  

(1)

Pshirkov and Postnov (2010) also considered coherent emission by magnetic-breaking energy loss, but they considered a strongly amplified magnetic field \((\sim 10^{15} \text{ G})\) to explain the luminosity \((\sim 10^{30-32} \text{ erg s}^{-1})\) of short gamma-ray bursts (GRBs), which are much brighter, but rarer than FRBs. We show below that FRBs can be explained without suggesting strong \(B\) field amplification, though a significant fraction of NS–NS merger events should produce FRBs.

3. Rate and Expected Radio Flux

The rate of FRBs is estimated to be \(1.0_{-0.5}^{+0.6} \times 10^4 \text{ d}^{-1} \text{ sky}^{-1}\) (Thornton et al. 2013), which is translated into a rate per unit comoving volume of \(2.3_{-1}^{+1.4} \times 10^4 \text{ yr}^{-1} \text{ Gpc}^{-3}\) to a comoving distance of \(D_{\text{comv}} = 3.3 \text{ Gpc}\), corresponding to a maximum redshift of \(z_{\text{max}} = 1\). This rate is statistically consistent with the "plausible optimistic estimate" of NS–NS mergers, \(\sim 10^4 \text{ yr}^{-1} \text{ Gpc}^{-3}\), as reviewed by Abadie et al. (2010). The FRB rate estimated from the four events is still statistically highly uncertain. Choosing a slightly larger value of \(z_{\text{max}}\) will further reduce the rate in proportion to \(D_{\text{comv}}^{-3}\). It should be noted that this comparison does not take into account the cosmological effects (the cosmological time dilation and merger rate evolution). An increase of the merger rate by a factor of \(\sim 4\) from \(z = 0\) to 1 is reasonable based on the cosmic star-formation history (Totani 1997; Dominik et al. 2013), which is a bigger effect than the cosmological time dilation, which reduces the observed rate by \(\propto (1 + z)^{-1}\), making the FRB rate closer to the standard "realistic" estimate of NS–NS mergers \((10^4 \text{ yr}^{-1} \text{ Gpc}^{-3})\). Therefore, the observed FRB rate is consistent with the NS–NS merger scenario, but the fraction of NS–NS mergers producing observable FRBs must be of order unity.

The coherent radio emission discussed above may be observed from most of the merger events, if the emission is not strongly beamed. A beaming fraction \(\Omega/(4\pi)\) of order unity is not unreasonable given the theoretical uncertainty about the beaming of pulsar radio emission (e.g., Kalogera et al. 2001), where \(\Omega\) is the total opening solid angle of radio emission. A direct, purely observational estimate based on the statistics of associations between pulsars and pulsar-powered nebulae indicates a beaming fraction of \(\sim 60\%\) for young pulsars (Frai & Moffett 1993).

Since the physics of coherent radio emission from pulsars is poorly understood (Lyubarsky 2008), we discuss the expected radio flux in terms of the ratio \(\epsilon_r\) of the radio luminosity, \(u L_r\), to the total energy loss rate, \(|\dot{E}|\). Although there is a large scatter of \(\epsilon_r\) for isolated radio pulsars in our Galaxy, we choose a typical value of \(\epsilon_r = 10^{-4}\) (Taylor et al. 1993; Manchester et al. 2005) at the rest-frame frequency, corresponding to the observed frequency, \(v_{\text{obs}} = 1.4 \text{ GHz}\). Using a luminosity distance, \(D_{\text{Lum}}\), to \(z = 0.75\), we obtain

\[
F_r = \frac{1}{v_{\text{obs}}} \frac{\epsilon_r |\dot{E}|}{4\pi D_{\text{Lum}}^2} = 0.02 \left( \frac{\epsilon_r}{10^{-4}} \right) \left( \frac{D_{\text{Lum}}}{4.6 \text{ Gpc}} \right)^{-2} \times \left( \frac{B}{10^{12.5} \text{ G}} \right)^2 \left( \frac{R}{10 \text{ km}} \right)^{6} \left( \frac{P}{0.5 \text{ ms}} \right)^{-4} \text{ Jy}.
\]

(2)

Therefore, the observed FRB fluxes \((\sim 0.5 \text{ Jy})\) can be explained by a slightly higher radio emission efficiency of \(\epsilon_r \sim 10^{-3}\), or a modest amplification of the magnetic field strength to \(B \sim 10^{13} \text{ G}\), but a very strong magnetic field, such as \(10^{15} \text{ G}\), is not necessary if \(\epsilon_r\) is similar to those for isolated radio pulsars. If the magnetic fields of binary neutron stars before a merger are much weaker than \(10^{13} \text{ G}\) as a result of magnetic field decays, amplification in a merged object would be required, though the decay of magnetic fields in neutron stars is still highly uncertain (e.g., Mukherjee & Kembhavi 1997).

4. Discussion

Several predictions and implications can be easily derived based on the hypothesis proposed here.

The NS–NS merger rate must be close to the optimistic (but still plausible) estimate, which is certainly good news to gravitational wave astronomy. The "plausible optimistic estimate" of the NS–NS merger rate in Abadie et al. (2010) is still one order of magnitude lower than the current upper limit (Abadie et al. 2012), but such a high rate predicts a detection within a few years in the early commissioning phase of the Advanced LIGO, whose ultimate detection rate would be \(\sim 400 \text{ yr}^{-1}\) to \(\sim 200 \text{ Mpc}\) (Abadie et al. 2010; Aasi et al. 2013). A typical radio flux of FRBs at 200 Mpc would be about 100 Jy, though a large scatter of radio flux from event
to event is expected due to the variation of $\epsilon_r$, as inferred from radio pulsars. An important advantage of FRBs compared with longer time-scale EM signals of NS–NS mergers is that FRBs tell us the exact time of coalescence. If a nearby/bright FRB sample is constructed based on future radio transient surveys, searching for gravitational wave bursts correlated with FRBs would significantly improve the effective sensitivity of gravitational wave detectors, allowing one to detect more distant mergers. Another advantage of FRBs for gravitational wave astronomy is that they are expected to be observable for most NS–NS merger events, in contrast to e.g., short GRBs.

If host galaxies are identified for FRBs, they should include early type galaxies that are not star forming, while the SGR or supermassive neutron-star scenarios predict only star-forming galaxies. Since FRBs can be observed to more distant universe than gravitational wave bursts, the cosmological-rate evolution of NS–NS mergers and its relation to host-galaxy evolution may be studied in the future, which would be complementary to short GRBs (if they are also produced by NS–NS mergers). The detectability of FRBs at other wavelengths is also of interest. The pulsed gamma-ray luminosity of pulsars is typically $\sim 10\%$ of the spin-down luminosity (Abdo et al. 2010), and millisecond duration gamma-ray emission from FRBs may be detected by GRB satellites. Assuming $\epsilon_r/\epsilon_l = 10^3$ for the gamma-ray band, a typical radio flux of $0.5\text{Jy}$ at $1.4\text{GHz}$ corresponds to a gamma-ray flux of $\nu F_\gamma \approx 7 \times 10^{-12}\text{erg cm}^{-2}\text{s}^{-1}$, which is much fainter than the typical Swift trigger threshold of $10^{-8}\text{erg cm}^{-2}\text{s}^{-1}$ in the $15$–$150\text{keV}$ band (Sakamoto et al. 2011). Note that the flux threshold for millisecond duration bursts should be much higher than this (T. Sakamoto 2013 private communication). The $50$–$300\text{keV}$ flux threshold of BATSE GRBs in the $64\text{ms}$ trigger window is $\sim 10^{-7}\text{erg cm}^{-2}\text{s}^{-1}$ (Fishman et al. 1994), and FRBs of $1\text{ms}$ duration must be very close to be detected by this trigger condition, but the expected event rate in such a small volume is extremely small. A search optimized for millisecond duration bursts in the past GRB data may be interesting.

If short GRBs are also produced by NS–NS mergers, their small rate ($\sim 10^{-7}\text{Gpc}^{-3}$; Coward et al. 2012) compared with FRBs indicates that only a tiny fraction of NS–NS merger events produce observable short GRBs. This is possible if short GRBs are strongly beamed, and/or they are produced by rarer events, such as large mass ratio binaries, mergers resulting in a hypermassive neutron star (HMNS) supported by rotation, or NS–BH/BH–BH mergers (Shibata & Taniguchi 2006; Faber & Rasio 2012). The beaming-corrected estimates of short GRB rate can be as high as $\sim 1000\text{yr}^{-1}\text{Gpc}^{-3}$ (Coward et al. 2012; Enrico Petrillo et al. 2013); if this is correct, about $10\%$ of NS–NS merger events are producing short GRBs to a certain direction. On the other hand, our hypothesis predicts that most of short GRBs must be associated with FRBs. The time delay by dispersion is about $1\text{ s}$ at GHz bands, but a longer time delay at lower frequencies may allow one to detect FRBs by follow-up searches after short GRBs (Lipunov et al. 1999; Pshirkov & Postnov 2010).

High time resolution observations of bright FRBs may reveal quasi-oscillatory behavior, reflecting the binary orbital period or rotation rate of merged objects, though numerical studies are necessary to make quantitative predictions. (However, scattering tails produced by propagation in the intergalactic medium may smooth out such fine temporal features.) The observed short duration implies that merged neutron stars should prompt form a BH on a dynamical time scale. This picture is consistent with the latest numerical simulations of NS–NS mergers, but a fraction of merger events may form an HMNS that survives for a time scale longer than milliseconds before collapsing into a BH (Hotokezaka et al. 2011; Faber & Rasio 2012). Such an HMNS may radiate a pulsar-like periodic coherent emission during its lifetime, and the fraction of such relatively long FRBs may give constraints on the mass distribution of NS–NS binaries and the equation of state at nuclear densities.

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