Radio precursors to neutron star binary mergings

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Abstract We discuss a possible generation of radio bursts preceding final stages of binary neutron star mergings which can be accompanied by short gamma-ray bursts. Detection of such bursts appear to be advantageous in the low-frequency radio band due to a time delay of ten to several hundred seconds required for radio signal to propagate in the ionized intergalactic medium. This delay makes it possible to use short gamma-ray burst alerts to promptly monitor specific regions on the sky by low-frequency radio facilities, especially by LOFAR. To estimate the strength of the radio signal, we assume a power-law dependence of the radio luminosity on the total energy release in a magnetically dominated outflow, as found in millisecond pulsars. Based on the planned LOFAR sensitivity at 120 MHz, we estimate that the LOFAR detection rate of such radio transients could be about several events per month from redshifts up to $z \sim 1.3$ in the most optimistic scenario. The LOFAR ability to detect such events would crucially depend on exact efficiency of low-frequency radio emission mechanism.

Keywords gamma-rays: bursts, binaries: close, pulsars: general, stars: neutron

1 Introduction

Despite the decade of active researches, cosmic gamma-ray bursts (GRBs) remain in the focus of modern astrophysical studies. A huge electromagnetic energy output of $\sim 10^{48} - 10^{53}$ ergs observed in GRBs requires gravitational or rotational energy release possibly mediated by magnetic field under extreme conditions (e.g., core collapse of massive rotating stars, binary neutron star (NS) or NS – black hole (BH) binary mergings). Among many possibilities, the concept of collapsar (Woosley 1993) for long GRBs (LGRBs) and compact binary mergings for short GRBs (SGRBs) (e.g. Blinnikov et al. (1984); Eichler et al. (1989), see a review by Nakar (2007)) appear to be the most viable ones. However, we are apparently still far from full understanding of these most energetic transient natural phenomena (see, e.g., the recent critical discussion by Lyutikov (2009)).

A magnetic mechanism may be required to explain the rich phenomenology of GRBs (e.g. Barkov and Komissarov (2008)). A BH surrounded by magnetized torus seems to be the prerequisite condition to form a GRB, since collimated relativistic outflows can not be produced by electromagnetic mechanism without external pressure (Lyubarsky 2010).

It is very challenging to seek for various messengers from complicated physical processes involved, such as gravitational-wave bursts (Sengupta et al. 2009) expected from compact binary mergings, active neutrino emission (Ruffert et al. 1997) and afterglows in the broad range of electromagnetic frequencies from radio and optics to x-ray (Kann and Klose 2008; Nysewander et al. 2009). The GRB afterglows are associated with the interaction of the relativistic GRB ejecta with the surrounding medium (see e.g. Hurley et al. (2006) for a review) and will not be considered here.

In the hard electromagnetic domain, the so-called GRB precursors preceding the main burst are found for a sizeable fraction of long GRBs with spectral properties similar to the main GRB emission (see Burlon et al. (2008), but none has been detected so far for short GRBs. Yet there are prospects for radio precursors
for the merging of magnetized binary NS as well (e.g. Lipunov and Panchenko 1996; Hansen and Lyutikov 2001; Moortgat and Kuipers 2003). If low-frequency radio emission can be generated prior to a SGRB, due to the dispersion in the intergalactic plasma the radio signal would arrive later than the gamma-ray pulse (Lipunova et al. 1997). So the GRB itself may be used as a trigger to search for such radio transient.

In this paper we would like to consider yet another possibility of the formation of non-thermal low-frequency radio emission that can be generated in relativistic plasma outflow prior to the final collapse of a binary neutron star. In contrast to the previous work by Hansen & Lyutikov, in which magnetospheric pair plasma generation was considered before the destruction of merging neutron stars, we shall investigate the next phase of the merging when a single differentially rotating object is formed and when the magnetic field can be amplified to magnetar values.

Our motivations for focusing on low-frequency radio emission are twofold. First, the lower the frequency, the longer is the intergalactic delay and the more time is accessible for a radio telescope to point to the GRB position. At frequencies above 1 GHz the delay is about a few seconds, which is insufficient for re-pointing of a large dish. The second motivation is stimulated by the approaching start of operation of the LOFAR radio telescope, which will have a record high sensitivity in the low-frequency range and whose design allows one to react to alerts with the necessary rapidity (Fender et al. 2008; van Leeuwen and Stappers 2010; van Leeuwen and LOFAR Transients Key Science Project 2009).

Our further considerations are based on the following three assumptions: (i) SGRBs are produced by binary NS mergers; (ii) an ultra-strong magnetic field ($\sim 10^{15} - 10^{16}$ G) is needed to power the GRB engine; (iii) a rapidly rotating pre-GRB object with strong magnetic field which is formed immediately after the merging can radiate in radio waves very much the same as usual pulsar.

Neutron stars are known to have strong magnetic fields that can survive through long time of the NS life (e.g. internal toroidal field, Abdolrahimi 2004). It is quite natural that these fields could give rise to various electromagnetic phenomena during final stages of the binary NS coalescence.

Binary NS population with the time prior to the coalescence due to gravitational wave emission less than the age of the Universe is known from binary pulsar observations (Regimbau et al. 2005). The rate of binary NS mergings is estimated to be quite high, $R_{\text{NS}} \sim 10^2 - 10^3$ Gpc$^{-3}$yr$^{-1}$ (see Postnov and Yungelson 2006 for a review), which is about two order of magnitudes higher than the estimated rate of SGRBs: $R_{\text{SGRBs}} \sim 1 - 10$ Gpc$^{-3}$yr$^{-1}$ (Nakar 2007). This discrepancy, of course, is not dangerous for binary NS mergings as the SGRB model considering narrow gamma-ray beaming and the possibility that not every merging ends up with a burst because of lack of required physical conditions (insufficient magnetic field, low mass, etc.).

Bursting electromagnetic emission can be generated at different stages of the merging process. First, a joint magnetosphere of two coalescing NSs can be restructured to produce strong flares from reconnection of magnetic lines (this process should be considered separately and will be discussed elsewhere). Next, during several last orbital revolutions before the merging the magnetospheric plasma effects come into play (e.g. Lipunov and Panchenko 1996; Hansen and Lyutikov 2001). Simulations show that after the merging a massive object with rapid differential rotation is formed (Shibata et al. 2005; Rasio et al. 2005; Faber et al. 2006), see review by Duez (2009). This object can not immediately collapse into BH until it gets rid of excessive angular momentum via some mechanism. At this stage a significant increase of the seed magnetic fields of NSs can occur: the energy of the differential rotation can be effectively transformed into the energy of magnetic field. Here the situation may be similar to what is thought to occur during the NS formation in the core collapse supernovae (Spruit 2008).

The growing magnetic field and rapid rotation can lead to the relativistic plasma generation and the formation of the outflow along the open magnetic field lines, in which pulsar-like low-frequency radiation can be produced. As we shall see, such a rapidly rotating strongly magnetized object can have much higher radio luminosity than even the brightest ordinary pulsars. Finally, the merging remnant can collapse into a BH (provided that its mass is above the maximum mass of a NS), possibly surrounded by a magnetized torus; such a configuration is favorable for the launch of a GRB.

2 Magnetic field amplification

First we address the question of the magnetic field amplification after the merging which is absolutely necessary for significant radio-emission generation.

Full MHD-simulations of the merging process in GR are extremely complicated and have not been performed as yet (Duez 2009), so we have to use crude semi-qualitative estimates.
The magnetic field amplification in the differentially rotating configuration occurs at the expense of the energy contained in the differential rotation and can be estimated as [Spruit 2008]:

\[ B^2 R^3 \sim \left( \frac{\Delta \Omega}{\Omega} \right)^2 \Delta E, \]  

(1)

where \( R \) is the characteristic radius of the region occupied by the strong magnetic field, \( R \approx 10^6 \) cm in our case, \( \Delta \Omega / \Omega \) is the factor characterizing the differential rotation and \( \Delta E \) is the full rotational energy. For binary NS mergings we expect

\[ \Delta E \sim E_{\text{orb}} \sim 10^{53} \text{ erg}. \]

This estimate shows that the magnetic field amplified during the binary NS coalescence can in principle be by an order of magnitude higher than the NS magnetic field generated in stellar core collapses:

\[ \frac{B_{\text{coal}}}{B_{\text{SN}}} \sim \frac{\Delta E_{\text{coal}}}{\Delta E_{\text{SN}}} \sim \frac{10^{53} \text{ erg}}{10^{51} \text{ erg}} \sim 100, \]  

(2)

Taking as granted a magnetar field (\( \sim 10^{15} \) G), we arrive at a fiducial value of \( B_{\text{max}} = 10^{16} \) G during the NS merging. These considerations are backed with recent numerical simulations [Duez et al. 2006]. Some models predict even larger values of the resulting field [Usov (1992)], up to \( 10^{17} \) G, but for conservative estimates we shall not use them.

The amplification of the poloidal field in the differentially rotating post-merger configuration may occur linearly (due to magnetic winding) or exponentially (due to magneto-rotational instability) [Duez et al. 2006]. The actual value of the maximal field attained depends on time available in the differentially rotating configuration: e.g., it can be destroyed by vigorous emission of gravitational waves in case if it was not precisely axial symmetric; such bar-like configurations may emerge in case of stiff EoS [Shibata et al. 2003]. Also, if it can survive long enough, the field can be amplified to the limits imposed by some external factor, e.g., the hydrostatic magnetic buoyancy [Kluźniak and Ruderman 1998] – a toroidal configuration with strong magnetic field can float to the surface, thus effectively stopping further enhancement of the field.

The energy loss rate in a magnetically driven outflow \( \dot{E}_m \) depends on the magnitude of the amplified field \( B \), the characteristic angular rotation frequency \( \Omega \) and the size of the object \( R \):

\[ \dot{E}_m \sim \frac{\Omega^4 B^2 R^6}{c^3} \]  

(3)

To be associated with the electromagnetic luminosity of GRBs \( \dot{E}_{\text{GRB}} = \dot{E}_m \), for typical values \( R \sim 10^6 \) cm and \( \Omega \sim 4000 – 6000 \) the magnetic field must fall within the range

\[ B \sim (10^{14} – 10^{16}) \text{ G}. \]  

(4)

This estimate is in agreement with the expected field during the merging process.

Numerical simulations of binary NS mergings by [Kiuchi et al. (2009)] suggest the time prior to collapse of order of a few ten ms almost independently on the initial conditions. Assuming the field amplification time to be the same for all SGRBs, the final distribution of magnetic fields should follow the initial one. This statement seems to be implicitly confirmed by the similarity between the observed SGRBs luminosity function and the distribution of magnetic field in coalescing binary NS prior to the merging [Postnov and Kuranov 2009].

3 Observations of rapidly rotating magnetar with LOFAR

A rapidly rotating post-merger object with strong magnetic field may generate low-frequency radio emission by the same physical mechanism as in ordinary pulsars. The exact mechanism of production of pulsar radio emission is a matter of debates (see e.g. Lyubarsky (2008) for a review), so we will treat the problem phenomenologically and assume that the radio luminosity is proportional to the total rotational energy losses

\[ L_{\text{rad}} = \eta \dot{E}, \]  

(5)

with the conversion coefficient \( \eta \) being a function of the total energy loss rate \( \dot{E} \). Using plots shown in Figure 11 for further estimates we adopted the power-law dependence

\[ \eta(\dot{E}) = 10^{-5} \left( \frac{\dot{E}}{10^{35} \text{ erg s}^{-1}} \right)^\gamma, \]  

(6)

with \(-1/2 < \gamma < 0\). The lower bound -1/2 (i.e. \( \eta \sim 1/\sqrt{\dot{E}} \)) can be derived from the efficiency of the secondary pair production mechanism in ordinary pulsars [Lyubarsky 2008].

For estimates of the emerging radio flux, we adopt a power-law radio spectrum with index \( \alpha = -2: F(f) \propto f^{-2} \). In our estimates we assume \( \dot{E} = 10^{50-52} \) erg s\(^{-1}\). Then the expected radio flux density at the fiducial lower cut-off frequency 100 MHz will be

\[ F \sim 8 \cdot 10^{3+15\gamma} \dot{E}_{50}^{1+\gamma} \left( \frac{1 \text{ Gpc}}{D} \right)^2 \text{ Jy}. \]  

(7)
where $E_{50} = \dot{E}/10^{50}\text{ergs}^{-1}$.

The duration of the radio pulse will be shorter than the time between the merging and the final collapse to BH, i.e. a few tens of ms. It is not excluded that the enigmatic ms radio transient reported by Lorimer et al. (2007) actually originated from the binary NS coalescence event.

Can such a bright short radio transient event be detected by LOFAR? Bearing in mind the assumed power-law spectrum we are primarily interested in the 120 MHz band of the High-Band Antenna (HBA) of LOFAR. Low-frequency radio observations are hampered with effects of propagation in the interstellar and intergalactic medium, especially due to strong dispersion and time scattering. The first effect can be treated by means of de-dispersion, at the same time providing convincing argument about extragalactic origin of the transient; moreover, only time delay due to the interstellar/intergalactic dispersion makes the observation of the precursor after GRB-alert possible. On the contrary, the interstellar/intergalactic scattering has purely devastating effect on the observations, irreversibly smearing short pulses. This broadening very strongly depends on the frequency of observations $\tau_{\text{sc}} \propto f^{-4}$. So a pulse with intrinsic width $\sim 10$ ms and flux density $\sim 10^5(D/1\text{ Gpc})^2$ s and the resulting flux density will be reduced:

$$F_{\text{obs}}(120\text{ MHz}) \sim 6 \cdot 10^{2+15\gamma}E_{50}^{1+\gamma} \left(\frac{1\text{ Gpc}}{D}\right)^4 \text{ mJy}$$  \(8\)

Using LOFAR parameters from Nijboer and Pandey-Pommier (2009), we obtain for the configuration with 13 core + 7 remote stations the following sensitivity:

$$S_{13+7} = 40 \left(\frac{SNR}{10}\right) \left(\frac{D}{1\text{ Gpc}}\right)^{-1} \left(\frac{\Delta f}{4\text{ MHz}}\right)^{-1/2} \text{ mJy},$$ \(9\)

where $\Delta f$ is the bandwidth. The maximal distance $D$ from which radio precursor can be detected by LOFAR gives us the rate of SGRBs with the assumed total energy release:

$$D = \left(1.5 \cdot 10^{1+15\gamma}E_{50}^{1+\gamma}\right)^{1/3} \text{ Gpc}$$  \(10\)

According to the BATSE catalog, the SGRB rate is about 170 per year (Meegan et al. 1997), around 30 per cent of them are found at redshifts smaller than $z = 0.2$.

\footnote{It is possible, however, that the duration can be extended up to a few seconds in some models (Duez 2009). In that case the observed radio signal would be two-three orders of magnitude brighter.}
(\(D = 1\) Gpc) \cite{Guetta and Piran 2006}; we have used these figures to obtain the expected rate of LOFAR detections shown in Fig. 2.

4 Conclusions

A binary NS coalescence leads to the formation of a differentially rotating massive object which can eventually collapse to BH possibly surrounded by a magnetized torus. Numerical simulations show \cite{Duez et al 2006} that the magnetic field is strongly amplified at the pre-collapse stage up to \(10^{15} - 10^{16}\) G. This configuration is favorable for the formation of a short gamma-ray burst.

At the stage preceding the collapse and GRB, a relativistic plasma outflow can be produced by the differentially rotating strongly magnetized configuration. Some fraction of the total power of this outflow can be converted to electromagnetic radio emission. The main uncertainty in the estimation of the radio luminosity before the collapse of this configuration is the unknown efficiency \(\eta\) of the conversion of the rotational energy losses from the differentially rotating pre-collapse object into radio emission, which we assumed to depend on the total energy loss rate as \(\eta \propto (\dot{E})^{\gamma}\) in analogy with millisecond radio pulsars. We have shown that in the most optimistic case the planned LOFAR sensitivity at 120 MHz allows the potential detection at the signal-to-noise ratio level > 10 of short (the proper duration of order of 10-100 ms, smeared by scattering in the intergalactic medium to \(~100\) s) radio bursts associated with SGRBs from redshifts \(z < 1.3\) at a rate of \(~90\) events/year. For an assumed dispersion measure of 1000 cm\(^{-3}\)pc, the low-frequency 120 MHz radio bursts should be delayed by 290 s with respect to the prompt gamma-ray emission, which enables one to use SGRB alerts for rapid redirecting the LOFAR synthesized beam to the SGRB position on the sky.

The detection of non-thermal radio bursts associated with short GRBs will strongly indicate the involvement of high magnetic field in the GRB engine. The dispersion measure of such a burst obtained from radio observations will give an independent direct estimate of the GRB distance. Radio precursors to short GRBs detected by LOFAR will open up an interesting possibility to search for such transients in LOFAR all-sky surveys. Short radio transients with similar characteristics can be a signature of ‘orphan’ SGRBs. This information can also be used in the analysis of data obtained by modern gravitational wave detectors.

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