Search for Pre-Burst Emission from Binary Neutron Star Mergers with Spectrum–Roentgen–Gamma

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Abstract—Close binary systems consisting of two neutron stars (BNS) emit gravitational waves, that allow them to merge on timescales shorter than Hubble time. It is widely believed, that NS–NS mergers in such systems power short gamma-ray bursts (GRB). Several mechanisms which could lead to electromagnetic energy release prior to a merger have been proposed. We estimate the ability to observe the possible pre-burst emission with telescopes of Spectrum–Roentgen–Gamma. We also investigate first such event, GRB210919A, which fell into the field of view of the SRG telescopes less than two days before the burst.

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1. INTRODUCTION

Short gamma-ray bursts (SGRBs) are narrow pulses of X-ray and gamma-rays, lasting typically for less than a second (up to several tens of seconds in some extreme cases, Rastinejad et al. 2022) which constitute a significant, although lesser part of the total gamma-ray burst population (Mazets and Golenetskii 1981; Kouveliotou et al. 1993; Svinkin et al. 2016; von Kienlin et al. 2020).

Thanks to the recent simultaneous gravitational wave (GW)/gamma-ray detection of such an event GW170817 (Abbott et al. 2017) (see, also, Pozanenko et al. 2020 for the claimed detection of the second similar event S190425z) the origin of at least some part of SGRBs are now secured. They are produced during neutron star–neutron star (NS–NS) mergers in binary systems: rapid inspiral generates characteristic “chirp,” observed in GWs, while relativistic jets from a newly-born black hole (BH) powers the observed γ- and X-ray emission (Rezzolla et al. 2011; Ruiz et al. 2016). At later stages the optical transient (so-called “kilonova” (Li and Paczynski 1998; Metzger 2019) are expected to arise, powered by a radioactive decay of neutron-rich nuclei, which condensed from the NS debris matter. It should be noted, that there was proposed another possible mechanism that explains electromagnetic emission from closing in NSs. In “tidal stripping” scenario (Clark and Eardley 1977; Blinnikov et al. 1984) instead of merging, part of the matter from one of the NS is accreted onto the other. As a result of this accretion, one of the NS loses matter until its mass reaches critical value and then it explodes (Blinnikov et al. 2021).

One of interesting possibilities in tight NS–NS binaries (BNS) is that there could be mechanisms that lead to the energy release prior to a merging. In fact, at least on short timescales (≈1 s before GRB) such events—so-called precursors—are observed (Koshut et al. 1995), although rarely, less then for 1% of SGRBs (Minaev and Pozanenko 2017). The origin of these precursors are not clear, although some authors connect them to crustal failures, caused by mutual tidal interactions (Tsang et al. 2012; Suvorov and Kokkotas 2020), while others suspect interactions between NS magnetospheres (Hansen, Luu-
There is also a proposed class of common envelope jet supernova (CEJSN); Gilkis et al. 2019 in which BNS could merge inside the envelope of a red giant star (RGS). This type of transients could produce a bright emission in broad wavelength range from optical to X-rays for months before the merging (Soker 2021). Although, it is necessary to note that in order to produce a “classical” short γ-ray burst in this scenario some fine-tuning is required for the merging to occur close to the RGS surface.

Due to its unpredictable occurrence, no strong upper limits on the pre-merger emission from BNS on longer timescales (days to thousands of seconds) have ever been published. In this Letter we show that the SRG (Sunyaev et al. 2021) observatory have a sufficient chance to observe BNS in their last hours days before the merging. We also discuss short GRB210919A, which was observed by SRG less than two days before the burst.

2. POSSIBILITY TO OBSERVE PRE-MERGER EMISSION FROM BNS WITH SRG

Observations of BNS in last days before the merging can be only serendipitous. Given its survey strategy, SRG is the most suitable observatory for such observations. Covering about 1% of sky each day, the Mikhail Pavlinsky ART-XC (Pavlinsky et al. 2021) and eROSITA (Predehl et al. 2021) telescopes have the highest chance to observe the position of upcoming transient among the sensitive grazing-mirror telescopes.

However, in order to recognise the observed X-ray transient as a pre-merging event, some kind of an external trigger is needed. It could be the detection of a well localised SGRB or a kilonova in the optical/near-IR band. The current generation of space-based gamma-ray burst monitors detects ≈40 SGRBs per year, although only Swift can provide accurate enough positions to search for the corresponding X-ray transients. The latest Swift/BAT GRB catalog1 (for details, Lin et al. 2016) suggests that over nearly 17 years of observations approximately 90 SGRBs were localised with Swift/XRT, given an estimated rate of 3.5 events per year. Optical surveys, such as Zwicky Transient Facility (ZTF, Bellm et al. 2019) or upcoming Large Synoptic Survey Telescope (LSST, Ivezić et al. 2019) could provide additional targets, including off-axis events (such as GW170817 Margutti et al. 2017; Pozanenko et al. 2018), that are biased against the detection by γ-ray monitors, due to their faintness. Andreoni et al. (2021) predicts that LSST could find 0.3–3.2 kilonovae per year with a specifically tailored observational program. No viable candidates were found in 23 months of ZTF data (Andreoni et al. 2020).

Therefore, it is straightforward to estimate that during its four-year survey, SRG will serendipitously cover the position of ≈0.2 upcoming SGRBs inside one-day window before the merging. This rough estimate agrees well with earlier estimates on the sGRB afterglow detection rate of ≈0.1 yr−1 Khabibullin et al. (2012).

Moreover, we could estimate total number of such transients detected in all-sky survey in local Universe (neglecting cosmological effects) by fixing pre-burst luminosity at one day before the burst and also assuming that emission is isotropic. If X-ray luminosity of the pre-burst emission is \( L_{X,42} \) (in units of \( 10^{42} \) erg s\(^{-1}\)) in 0.2–2.3 keV band, in which eRosita have typical sensitivity of \( F_X = 10^{-13} \) erg cm s\(^{-1}\) in a day, \( A_{sky} = 360/41253 \approx 0.009 \) — part of sky, covered per day and \( R_{NS-NS} = 10–1700 \) Gpc\(^{-3}\) year\(^{-1}\) is a BNS merger rate (measured during first three observing runs with LIGO-Virgo, The LIGO Scientific Collaboration, the Virgo Collaboration et al., 2021). Then, in volume of \( V = 0.1 L_{X,42}^{3/4} \) Gpc\(^3\) we could expect to see \( N_{observed} \approx V \times A_{sky} \times R_{NS-NS} \) events year\(^{-1}\). For pre-merger luminosity of \( 10^{42} \) erg s\(^{-1}\) we, therefore, could expect between 0.01–2 events per year.

However, it should be noted, that it would be tricky to distinguish such events from other transients, routinely seen by SRG, such as flares on nearby stars, AGN variability, etc.

3. GRB210919A

The GRB210919A was first detected by Swift/BAT on 00:28:33 UT, September 19, 2021 (Tohuvavohu et al. 2021), and was soon observed with Swift/XRT. This observation allowed to obtain the precise localisation of the soft X-ray afterglow with coordinates of RA, Dec = 80.25448 + 1.31153 (FK5, J2000, the 90% confidence radius is 4.6″, Goad et al. 2021). Follow-up observations in optical/near-IR wavebands found no bright transient sources inside Swift/XRT error region (Perley et al. 2021; Zhang et al. 2021; Gottlieb et al. 2021; Pierel et al. 2021; Kann et al. 2021c), however, a single weak
NIR source was observed (with \( \nu' = 24.14 \pm 0.30, R_c = 24.47 \pm 0.53 \) magnitude in AB system Kann et al. 2021b, 2021c), which soon faded (Kann et al. 2021a). Deep imaging of the GRB field revealed two galaxies with 20.5 and 24 magnitude in \( r \)-band (AB, O’Connor et al. 2022), located at same redshift \( z = 0.2411 \) (Rossi et al. 2022). Projected distance between the faded optical source and these galaxies is 13 or 50 kpc, assuming that the optical transient lies on same redshift. Such distances from host galaxy are typical for short GRBs (see, e.g., Fong and Berger 2013; Berger 2014 and references therein), and usually explained by velocity kicks received during the supernova explosion of one of the components (Fryer and Kalogera 1997). All of this lead us to proposition, that the observed NIR transient was an afterglow of GRB210919A and the merger happened in group of galaxies at \( z = 0.2411 \). A deep \textit{Chandra} observation performed \( \approx 2 \) days after the burst also failed to detect an afterglow (Sakamoto et al. 2021).

In order to show the temporal evolution of the GRB X-ray emission, we translated all observed fluxes to the 0.3–10 keV energy band, assuming that at every moment the event spectrum is described by a simple absorbed power-law model with an absorption column thickness of \( 1.6 \times 10^{21} \text{ cm}^{-2} \) (Willingale et al. 2013). For the main impulse we used \( \Gamma = 1.58 \) (Barthelmy et al. 2021), as it was measured by Swift/BAT. Swift/XRT data were processed with the online analysis tool (Evans et al. 2009). During the prompt Swift/XRT observation the afterglow was detected with the flux of \( 4.5 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \). The source spectrum was consistent with the absorbed power-law with the absorbing column thickness close to the Galactic value and a power-law index of \( 2.1^{+1.1}_{-1.2} \).

There were several late-time follow-up observations: two by Swift/XRT, started approximately 5 ks and 280 ks after the burst, and a rapid \textit{Chandra} target-of-opportunity observation, that lasted for 20 ks and started 180 ks after the burst. In all of these observations afterglow was not detected, with the stringent 3\( \sigma \)-upper limit on the source flux of \( 7.5 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \) in 0.3–10 keV band (Sakamoto et al. 2021), assuming that the spectrum has not changed after the first afterglow detection.

The ART-XC telescope covered the sky field of GRB210919A two days prior to the burst, with a mean time of about 1.9 days before the burst. We produced the calibrated event lists and sky images using the ARTPRODUCTS pipeline v0.9 with the CALDB version 20200401. No source was detected in the standard 4–12 keV energy band, nor in the harder 8–16 keV one. The corresponding 95% upper limits on the source flux are \( 6.5 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1} \) and \( 8.6 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1} \), respectively, assuming a Crab-like spectrum.

The field of GRB210919A was visited 8 times by eROSITA with a total exposure time of \( \approx 261 \text{ s} \) during eRASS4, starting from 13:13:46 UTC on September 16, 2021. Given its larger field of view, the last eROSITA visit of the source occurred significantly later than for ART-XC, on 17:13:48 UTC, September 17, 2021. We processed the data with the standard eROSITA Science Analysis Software System (eSASS, version eSASS_users201009) (Brummer et al. 2018) pipeline. Assuming that the spectrum is an absorbed power-law with a column density of \( 1.6 \times 10^{21} \text{ cm}^{-2} \) and a photon index of \( \Gamma = 1.9 \), we obtained a 3\( \sigma \) upper limit of \( 7.7 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \) in the soft 0.2–2.3 keV band.

Overall limits on pre-merger X-ray emission derived from SRG telescopes are shown in Fig. 1, and the combined lightcurve is presented in Fig. 2.

4. UPPER LIMITS ON LUMINOSITY OF PRE-MERGER BNS

As it was stated earlier, there is no direct measurement of the redshift of GRB210919A. The quality of the high-energy X-ray (\( \gtrsim 100 \text{ keV} \)) data is also insufficient to use Amati relation or similar (see Minaev and Pozanenko 2020, and references0 to assess the distance. Assuming that the discovered galaxy group at \( z = 0.2411 \) (\( D \approx 1.2 \text{ Gpc} \)) (O’Connor et al. 2021; Rossi et al. 2022) is, indeed, hosts the GRB progenitor system, we can place upper limits on its isotropic X-ray luminosity: \( L_{\text{eROSITA}} \leq 10^{43} \text{ erg s}^{-1} \), \( L_{\text{ART-XC}} \leq 10^{45} \text{ erg s}^{-1} \).

Now we can estimate the total isotropic-equivalent energy of the GRB as \( E_{\text{iso}} \approx 10^{50} \text{ erg} \), using measured fluence and extrapolating Swift/BAT spectrum. From proposed relation between \( E_{\text{iso}} \) and viewing angle (Salafia et al. 2019) one can assume that the initial binary system was seen nearly edge-on. For the standard 1.4 \( M_{\odot} \) masses of the components, the two-day time before the coalescence corresponds to an orbital separation of \( a_0 \sim 100 R_{\text{NS}} \sim 10^8 \text{ cm} \). This separation can be smaller than the light cylinder of one of the components, \( R_l = c/\nu = 5 \times 10^9 (P/1 \text{ s}) \text{ cm} \) (\( P \) is the NS spin period). In this case, the expected electromagnetic power is \( L_{\text{em}} \approx 10^{38} (B_9/10^{15} \text{ G})^2 (a_0/10^8 \text{ cm})^{-7} \text{ erg s}^{-1} \) (Hansen and Lyutikov 2001), where \( B_9 \) is the NS surface magnetic field. If the NS spin period is shorter, there may be the case where the NS magnetosphere size is smaller than the orbital separation. This configuration was considered in Wang et al. (2018). In the most favourable case of anti-aligned magnetic dipole moments of two NSs,
the expected electromagnetic power is $L_{\text{em}} \sim 4 \times 10^{41} (B_s/10^{12} \text{ G})^2 (a/10^8 \text{ cm})^{-2}$ erg s$^{-1}$. While the total power in this case can be commensurable with the eROSITA upper limits, the expected spectra are too soft to produce X-ray emission. Thus, the obtained X-ray upper limits are too loose to constrain the possible physical properties of the putative binary NS system two days before the merging.

5. CONCLUSIONS

Detection of pre-merger emission from merging BNS is a tempting, although complex observational task. However, thanks to its observational strategy telescopes on board SRG could detect such events during the all-sky survey. We have analysed observation of sGRB GRB210919A, that was observed by SRG less than two days before the merger. We have obtained, for the first time, upper limits on pre-merger X-ray emission on day-length timescales: assuming that the merger happened in galaxy group at $z = 0.2411$ upper limits are $L_{\text{eROSITA}} \leq 10^{43}$ erg s$^{-1}$ and $L_{\text{ART-XC}} \leq 10^{45}$ erg s$^{-1}$.

We have estimated, that during the 4 year survey SRG could observe about 0.2 sGRB serendipitously less than a day before the merger.

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