A Search for Hard X-Ray Bursts Occurring Simultaneously with Fast Radio Bursts in the Repeating FRB 121102

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Abstract

The nature of fast radio bursts (FRBs) is currently unknown. Repeating FRBs offer better observation opportunities than nonrepeating FRBs because their simultaneous multiwavelength counterparts might be identified. The magnetar flare model of FRBs is one of the most promising models that predict high-energy emission in addition to radio burst emission. To investigate such a possibility, we have searched for simultaneous and quasi-simultaneous short-term hard X-ray bursts in all Swift/BAT event mode data, which covered the periods when FRB detections were reported in the repeating FRB 121102, by making use of BAT’s arcminute-level spatial resolution and wide field of view. We did not find any significant hard X-ray bursts that occurred simultaneously with those radio bursts. We also investigated potential short X-ray bursts that occurred quasi-simultaneously with those radio bursts (occurrence time differs in the range from hundreds of seconds to thousands of seconds) and concluded that even the best candidates are consistent with background fluctuations. Therefore, our investigation concluded that there were no hard X-ray bursts detectable with Swift/BAT that occurred simultaneously or quasi-simultaneously with those FRBs in the repeating FRB 121102.

1. Introduction

The fast radio burst (FRB) is a recently recognized class of astrophysical transient phenomena (Lorimer et al. 2007; Thornton et al. 2013), featuring short durations (millisecond timescale), high flux densities (∼Jansky), and large dispersion measures (DMs) implying cosmological distances. The localization of several FRBs (Tendulkar et al. 2017; Bannister et al. 2019; Ravi et al. 2019) even certifies their cosmological origin. FRB 121102 is the first discovered repeating FRB (Spitler et al. 2014; Petroff et al. 2015; Scholz et al. 2016; Spitler et al. 2016). Afterward, the CHIME/FRB Collaboration (CHIME/FRB Collaboration et al. 2019a) discovered a second repeating one (FRB 180814.J0422+73; CHIME/FRB Collaboration et al. 2019b) and soon eight more (CHIME/FRB Collaboration et al. 2019c). Many of these repeating FRBs show common features in their bursts: complex burst morphology and sub-burst downward frequency drifts (CHIME/FRB Collaboration et al. 2019b, 2019c; Hesselis et al. 2019), although these features are also seen in some nonrepeating FRBs (e.g., Champion et al. 2016). The repetition in these sources naturally excludes cataclysmic models for them. However, the physical nature of either repeating or nonrepeating FRB sources is not clearly understood.

The repetition of FRB 121102 enabled its interferometric localization (R.A.: 05°31′58.70, decl.: +33°08′52.5; Chatterjee et al. 2017) and the identification of its host galaxy ($z = 0.19273$, $\sim$970 Mpc; Tendulkar et al. 2017). Its bursts show highly variable spectra (Scholz et al. 2016; Hesselis et al. 2019). Spitler et al. (2016) and Chatterjee et al. (2017) reported a DM of 558.1 ± 3.3 pc cm$^{-3}$. First of all, based on the tremendous energy released over milliseconds and the repetition of bursts, its nature is suspected to be related more to a young active neutron star, for example, the phenomena of magnetar flare and giant pulse (Popov & Postnov 2010; Kulkarni et al. 2014; Lyubarsky 2014; Connor et al. 2016). Second, the high rotation measures (RMs) of FRB 121102 ($>10^5$ rad m$^{-2}$; Michilli et al. 2018) indicate extreme magnetonic surroundings of the burst source, and the estimated magnetic field with such a high strength can be explained by that of a magnetar (for example, SGR J1745–2900;Eatough et al. 2013). Third, Tendulkar et al. (2017) identified the host galaxy of FRB 121102 as a compact (diameter $\lesssim$4 kpc) dwarf ($\sim$6 $\times$ 10$^7$ $M_{\odot}$), which is believed to be the crib of superluminous supernovae or long-duration gamma-ray bursts. They are likely the progenitor of a millisecond magnetar (Dai & Lu 1999; Zhang & Meszáros 2001; Kasen & Bildsten 2010; Woosley 2010; Yu et al. 2017), which is hence considered to be the origin of FRB 121102. Therefore, the young magnetars responsible for FRBs could be formed from some unusual core-collapse supernovae and are then harbored at the center of a supernova remnant (Murase et al. 2016; Kashiyma & Murase 2017; Metzger et al. 2017; Margalit & Metzger 2018; Metzger et al. 2019). For a more general consideration, these young magnetars could also be born from the mergers of double neutron stars (Dai et al. 2006; Metzger et al. 2008; Yu et al. 2018) or from the accretion-induced collapse of white dwarfs (Canal et al. 1990; Nomoto & Kondo 1991). This possibility at least has been somewhat supported by observations of nonrepeating FRBs (Cao et al. 2018; Margalit et al. 2019). In this case, the young magnetars cannot be associated with a supernova remnant but they can still be surrounded by a pulsar wind bubble (Dai et al. 2017). Therefore, no matter which channel the magnetars originate from, a persistent radio
counterpart emission can always be generated by the interactions between the ejecta, pulsar wind, and the surrounding medium. Using the flux of the persistent radio emission and the decreasing DM of FRB 121102 (i.e., a 10% decrease over seven months; Michilli et al. 2018), the age of the neutron star can be tightly constrained to be about 100 years old (Cao et al. 2017; Metzger et al. 2017). In view of its high relevance to a young magnetar, it is very natural to expect that FRB 121102 could be accompanied by some high-energy emissions.

The Swift/BAT can cover the entire sky as efficiently as 80%–90% per day (Krimm et al. 2013) and offers a time resolution of 10−4 s for trigger event mode data. It is good for detecting or monitoring short-and-bright X-ray transient sources and therefore meets the requirement for addressing the aforementioned scientific questions. A blind search for hard X-ray bursts in the BAT data of one year (2016 October 1 to 2017 September 30) had been conducted (Sun et al. 2019). Continuing previous efforts, we searched for X-ray bursts in all of the BAT trigger event mode data that were simultaneous with all of the radio bursts from FRB 121102 that had been reported in the literature. In addition to the search for simultaneous X-ray bursts, we also performed a search for possible bursts that did not occur simultaneously in these data. We present the method and our results achieved in our search for burst signals in the direction of FRB 121102 with the Swift/BAT data in Section 2. Then we discuss and conclude in Section 4.

2. Observations and Analysis

All FRBs in FRB 121102 that had been reported in the literature (from 2014 until 2019 August) were investigated. The sample and the corresponding references are listed in Table 1. We also referred to the paper of Li et al. (2019) where part of the sample was also collected. Because the radio bursts in repeating FRBs have a timescale of about milliseconds in the radio band, to search for high-energy short-term bursts in association with those radio bursts either simultaneously or quasi-simultaneously, we have to make use of the event mode data in the Swift/BAT archive. These BAT-triggered event mode data have a time resolution of about 100 μs, and the corresponding time stamp of each photon detected by BAT was recorded.

Table 1

| Reference                  | N$_{th}$ | Dates of Bursts | Radio Observatory$^{b}$ |
|----------------------------|----------|-----------------|-------------------------|
| Spitler et al. (2014)      | 1        | 2012 Nov 02     | AO                      |
| Spitler et al. (2016)      | 11       | 2012 Nov 02     | AO                      |
| Scholz et al. (2016)       | 6        | 2015 Nov 13     | AO, GBT                 |
| Spitler et al. (2018)      | 3        | 2016 Aug 20     | Effelsberg              |
| Law et al. (2017)          | 9        | 2016 Aug 23     | AO, VLA                 |
| Gourdji et al. (2019)      | 42       | 2016 Sep 13     | AO                      |
| Scholz et al. (2017)       | 13       | 2016 Sep 16     | AO, GTB                 |
| Michilli et al. (2018)     | 17       | 2016 Dec 25     | AO, GBT                 |
| Hardy et al. (2017)        | 13       | 2017 Jan 16     | Effelsberg              |
| MAGIC Collaboration et al. (2018) | 5    | 2017 Feb 15     | GBT                     |
| Zhang et al. (2018)        | 93       | 2017 Aug 26     | GBT                     |
| Josephy et al. (2019)      | 1        | 2018 Nov 19     | CHIME                   |

Notes.

$^{a}$ Number of detected bursts from FRB 121102.

$^{b}$ Arecibo Observatory (AO), Canadian Hydrogen Intensity Mapping Experiment (CHIME), Effelsberg Radio Telescope, Robert C. Byrd Green Bank Telescope (GBT), Very Large Array (VLA).

We first aimed to search for potential X-ray bursts that occurred simultaneously with those 234 fast radio bursts in the sample list in Table 1. Simultaneous BAT-triggered event mode data (spread over 14 observations of total exposure about 64 ks) were found to be available for 46 radio bursts in the sample. However, FRB 121102 was not always in the field of view of BAT during these 14 observations. It turns out that there was only one radio burst covered with simultaneous BAT exposure in observation 00085966015, so we further analyzed the data set in more detail. Beyond the investigation of BAT event data covering the radio burst, we also searched for any X-ray bursts that occurred before or after the radio bursts in the event data of those 14 observations when BAT’s field of view covered FRB 121102. This corresponds to a search for hard X-ray bursts when the repeating FRB was in active radio bursting phases.

The event mode data were processed by the software package HEASOFT v6.19 following the SWIFT BAT Software Guide. The BATDETMASK tasks were used to produce the detector quality map from CALDB. The BATDETMASK tasks calculate the mask weighting for each event file. The BATBINEVT tasks were run again to produce the light curves (LCs) from event files corresponding to the specified direction of FRB 121102 (R.A. 82°9946, decl. 33°1479) in the following four different energy bands, namely, 15–30, 30–60, 60–150, and 15–150 keV. To generate the sky maps, the BATBINEVT tasks were run to convert those event lists to detector plane images (DPIs), and the BATFFTIMAGE task was used to convert them into sky maps with photon counts or significance. As a result, the total exposure time of the event mode data toward FRB 121102 was about 2.1 ks. The FRBs have millisecond timescales in the radio band, and it is natural to search for their X-ray counterparts on millisecond timescales, but not limited to millisecond timescale alone. Our search for potential short-term bursts was conducted on four representative timescales, namely 1 ms, 10 ms, 100 ms, and 1000 ms. We decided our shortest timescale to be 1 ms because small binning results in plenty of
LC/image data and large uncertainty in flux, and hence demands more computing resources.

In Figures 1 and 2, we present the BAT LC (15–150 keV; time bin of millisecond) and sky image, which are simultaneous with the radio burst occurring on 2016 September 18 04:10:17.434 (referred to infinite frequency at the solar system barycenter) from FRB 121102 (reported by Scholz et al. 2017; see Table 1). We convert times between the satellite and the barycenter with BARYCORR in FTOOLS, taking into account the relative locations of the satellite, the geocenter, and the barycenter. The LC time marked in red in Figure 1 is the result of converting the FRB barycentric time to that at the Swift satellite. The significances of the two BAT rate measurements in the ±1 ms time window of the radio burst are both below 3σ as shown in the LC (see in Figure 1 the dashed lines for the average and ±3σ of the rates, and the red markers for the ±1 ms time window) and the sky image (see in Figure 2 the red color indicating significance below 3σ, and the magenta dashed circle marking the location of FRB 121102). Below we put constraints on the X-ray flux simultaneous with the radio burst. Conservatively, the measurement with a larger rate value and a larger uncertainty is used for estimating an upper limit of the flux. The 3σ upper limit of the count rate (±3× standard deviation of the rates; binned in milliseconds) we derived is 4.6 cts s⁻¹, which is equivalent to 6.9 × 10⁻⁷ erg cm⁻² s⁻¹ in the entire energy band of 15–150 keV if we assume an energy spectrum with a photo index of 2. The count rates in the 10 ms, 100 ms, and 1000 ms binned LCs at the radio burst time are checked, too. All of them are below 3σ of the rates, which correspond to 1.2, 0.38, and 0.091 cts s⁻¹.

For the processing of the event mode data, we refer to the methods described in paragraph 4, Section 2 of our previous paper, Sun et al. (2019). To avoid complexities due to bright sources entering into the BAT field of view, the following segments were excluded from the original BAT event data in our searches, based on which we are able to put an upper limit on our investigations:

1. large dips occasionally appearing in the LCs with an interval within one time bin and an amplitude larger than the standard deviation. After applying these two conditions, about 85% of the data remains, and
2. those segments with low signal-to-noise ratios (S/Ns): |count rate/statistical error| < 1.

Using these criteria, we obtained the actual segments of the event data for our burst search. We performed searches for potential X-ray bursts in the data sets on timescales of 1 ms, 10 ms, 100 ms, and 1000 ms, as described in paragraph 5, Section 2, of our previous paper, Sun et al. (2019).

After computing the fluences (Σpulse rate; called pulse integrals, PIs) of candidate bursts, we then checked those bursts with fluences above a certain threshold. In the current study, we set the fluence threshold to 0.0035 counts = 0.1 × crab rate × 1 s. To set up this criterion, we refer to the empirical rules used in the Swift/BAT project of transient monitoring, where sources are considered detected under the following circumstances: (a) the mean rate is at least 0.003 crab rate, or (b) the peak rate (one-day binned) for the source is at least 0.03 crab rate with at least a 3σ significance. When we applied 0.03 crab to our short-duration (1 s–1 ms) pulse search, there were too many noisy pulses from background fluctuation, so that we needed to enhance the threshold. Furthermore, we checked the S/N (Σpulse rate/√Σpulse error²) threshold of S/N = 5.0. Whenever there is a candidate burst above these two thresholds, a sky map corresponding to the specific time range is then generated to check whether the candidate burst has an astrophysical origin. In some cases, certain instrumental effects caused significant flux fluctuation at the edge of the sky map (due to small-portion illumination of the detectors by the sources at the edge of the field of view). In some cases, cosmi-
ray events probably caused widespread illumination of the detectors. We exclude these events and remove the corresponding time intervals in the LCs.

3. Results

As a result of searching in 1 ms, 10 ms, 100 ms, and 1000 ms timescales with the threshold of $S/N = 5.0$, there is no candidate passing all the filters. To be careful with our search, we select pulses with the highest $S/N$s to check what they look like. As we lower the threshold of the $S/N$ to 3.5, five pulses are left, as reported in Table 2. There is one found from the search in the 10 ms timescale; four from that in the 1 ms timescale. All of them have $S/N$s between 3.5 and 4, in observation 00050100039, which might be associated with the radio burst occurring at 2017 February 19 16:37:48.114137 (referenced to in finite frequency at the solar system barycenter) reported by Hardy et al. (2017). All of the pulses are found in this observation because the condition of BAT exposing toward FRB 121102 in this observation was the best among all. Among the five pulses, pulse 2 has the shortest separation of about 800 s after the radio burst. The other pulses have separations of about 930 s–7200 s. They all happen to be after the radio burst because the radio burst lies at the beginning of the BAT observation. We present the LCs and sky images for pulse 2 (1 ms timescale) in Figures 3 and 4. In the sky map of the X-ray pulse, we see that in the source direction, the significance indicated by the colors is only slightly higher than that in other regions, and we cannot regard them as astrophysical bursts.

To evaluate the statistical significance, we calculate the number of false positives above a given threshold to be expected from screening those BAT count rates below null by assuming that the count rates are affected by purely uncorrelated Gaussian noise. The number of false-positive pulses expected above the $S/N$ of 3.5 for the 10 ms timescale is 0.89, and for the 1 ms timescale, 7.6. The number of candidates from the search is one for the 10 ms timescale, and four for the 1 ms timescale. We find that the candidates are compatible with being statistical fluctuations.

4. Conclusions

We have searched for simultaneous short-duration hard X-ray bursts as well as quasi-simultaneous short-duration bursts in the direction of FRB 121102 in the Swift/BAT archival event mode data in which radio bursts were detected from FRB 121102. There were existing BAT X-ray event mode data taken simultaneously with a radio burst detected in FRB 121102. We exclude these events and remove the corresponding time intervals in the LCs.

| Pulse Timea | Pulse Integralb | Pulse S/Ne |
|-------------|-----------------|------------|
| Start Time (s) | Stop Time (s) | (cts) | |
| Search in 1 s binned and 0.1 s binned LCs |
| No candidate found |
| Search in 0.01 s binned LCs |
| 1 16539.365 | 16539.405d | 0.00762 | 3.63 |
| Search in 0.001 s binned LCs |
| 2 15627.204 | 15627.209d | 0.00500 | 3.77 |
| 3 16167.264 | 16167.269d | 0.00503 | 3.70 |
| 4 16567.854 | 16567.859d | 0.00449 | 3.69 |
| 5 22030.669 | 22030.674d | 0.00470 | 3.73 |

Notes.
a. Swift time in seconds - 509200000
b. $S_{\text{pulse}} = \sum_{i} \text{rate}_{i}$.
c. $S_{\text{pulse}} = \sum_{i} \text{pulse}_{i} / \sqrt{\sum_{i} \text{pulse}_{i} \text{error}_{i}^{2}}$. The pulse search was conducted with the following conditions: threshold of pulse integral 0.0035 = 0.1 x crab unit x 1 s; threshold of $S/N = 3.5$.
d. In observation 00050100039 (obs. id).

Figure 3. The BAT FRB 121102 LC before and after the X-ray pulse (in red markers) with the highest $S/N$ among the search results as reported in Table 2. Dashed lines denote the average and $\pm 3\sigma$ of the rates. See the BAT sky image of this pulse in Figure 4.

(a) X-ray pulse 2, ms timescale

Figure 4. The BAT sky image in the direction of FRB 121102 taken during the time periods of the X-ray pulse with the highest $S/N$ among the searches as reported in Table 2. The magenta dashed circle marks the nominal size of the point-spread function of BAT coded-mask imaging. See the BAT LC before, in, and after the moment in Figure 3.
121102, but there was no X-ray signal over 3σ found in the event of the radio burst. We are able to put an upper limit of $6.9 \times 10^{-7}$ erg cm$^{-2}$ s$^{-1}$ to a hard X-ray burst in the energy band 15–150 keV simultaneous with the radio burst from the repeating FRB 121102, assuming a photo index of 2. This limit on flux, converted into luminosity assuming isotropy and given the distance to the source ($\sim$970 Mpc; Tendulkar et al. 2017), is $7.8 \times 10^{49}$ erg s$^{-1}$. In conclusion, we have not found evidence that supports the source of FRB 121102 radiates strong hard X-ray burst emission detectable with current X-ray instrument like Swift/BAT simultaneously with those radio bursts.

We noticed that the recent detection of a bright radio burst (with two pulses) from the magnetar SGR 1935+2154 (Bochenek et al. 2020; Scholz & Chime/Frb Collaboration 2020) while it was in active bursting phase (including Swift/BAT; Palmer 2020) and subsequent identifications of its association with X-ray and soft gamma-rays bursts (Mereghetti et al. 2020; Tavani et al. 2020; Zhang et al. 2020) have confirmed that X-ray bursts or burst activities could be related to some FRBs in local distances. The measured count rate with BAT from SGR 1935+2154 was 350,000 cts s$^{-1}$ on a 1 s timescale over the full detector sensitivity range. If we consider putting it as far away as FRB 121102 (SGR 1935+2154: $< 10$ kpc; FRB 121102: $\sim 700$ Mpc; Kozlova et al. 2016; Tendulkar et al. 2017), then the predicted flux is still below the upper limit that we derived in this paper.

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