Observation of the Second LIGO/Virgo Event Connected with a Binary Neutron Star Merger S190425z in the Gamma-Ray Range

A. S. Pozanenko¹,²*, P. Yu. Minev¹, S. A. Grebenev¹, and I. V. Chelovekov¹

¹Space Research Institute, Russian Academy of Sciences, Profsoyuznaya ul. 84/32, Moscow, 117997 Russia
²National Research University "Higher School of Economics", Myasnitskaya ul. 20, Moscow, 101000 Russia

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Abstract—The results of observations of the gravitational-wave (GW) event S190425z recorded by the LIGO/Virgo detectors with the anti-coincidence shield (ACS) of the SPI gamma-ray spectrometer onboard the INTEGRAL observatory are presented. With a high probability (>99%) it was associated with a neutron star (NS) merger in a close binary system. This is only the second event of such a type in the history of gravitational-wave observations (after GW 170817). A weak gamma-ray burst, GRB 190425, consisting of two pulses ~0.5 and ~5.9 s after the NS merger in the event S190425z with an a priori significance of 3.5 and 4.4σ (taken together 5.5σ) was detected by SPI-ACS. Analysis of the SPI-ACS count rate history recorded on these days (a total of ~125 ks of observations) has shown that the rate of random occurrence of two close spikes with the characteristics of GRB 190425 does not exceed $6.4 \times 10^{-5} \text{ s}^{-1}$ (i.e., such events occur by chance, on average, every ~4.3 hours). Note that the time profile of GRB 190425 has much in common with the profile of GRB 170817A accompanying the event GW 170817, that both NS mergers were the nearest ($<150 \text{ Mpc}$) of all the events recorded by the LIGO/Virgo detectors, and that no significant excesses of the gamma-ray flux above the background were detected in any of ~30 black hole merger events recorded to date by these detectors. No bursts of hard radiation were detected in the field of view of the SPI and IBIS/ISGRI gamma-ray telescopes onboard INTEGRAL. This, along with the absence of detection of gamma-ray emission from GRB 190425 by the GBM gamma-ray burst monitor of the Fermi observatory suggesting its occultation by the Earth, allows the localization region for the source of this GW event to be reduced significantly. The parameters $E_{\text{iso}}$ and $E_p$ for GRB 190425 are estimated and compared with those for GRB 170817A.

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INTRODUCTION

The detection of the gravitational-wave signal GW 150914 from the merger of two black holes (Abbott et al. 2016) ushered in an era of GW astronomy. Over the past four years the Advanced LIGO GW detectors and the Advanced Virgo detector, which came into operation in August 2017, (hereafter simply LIGO and Virgo) have already recorded ~40 such events. The sensitivity of the detectors grows rapidly: only 3 events were recorded in the O1 cycle of LIGO operation (from September 12, 2015, to January 19, 2016), 8 events were recorded in the O2 cycle (from November 23, 2016, to August 25, 2017), and already 31 events were recorded in O3 (started on April 1, 2019) by late September 2019. The catalog of O1 and O2 events can be found in Abbott et al. (2019); the current list of O3 events is accessible at gracedb.ligo.org/superevents/public/O3.

The LIGO/Virgo detectors are optimized for the observation of signals from compact binary systems and, therefore, can successfully record not only binary black hole (BBH) mergers, but also neutron star—black hole (NSBH) binaries or binary neutron stars (BNS). The detection rate of various types of events depends on the examined volume of the local Universe and the number of binaries of a given type in this volume. The volume itself is proportional to the cube of the distance from which a signal with a minimum amplitude can be recorded, while the distance is proportional to the mass of the lightest binary component. Not surprisingly, the number of recorded BBH mergers far exceeds the number of NSBH and BNS mergers—at the time of submitting the paper two reliable (with a probability $\geq85\%$) signals from NSBH
(S190814bv and S190910d) and three from BNS (GW 170817, S190425z, S190901ap) were recorded; all of these binaries were located at noticeably shorter distances than the recorded BBH mergers.

An intensive search for bursts of electromagnetic radiation during and after each LIGO/Virgo event led only to one reliable detection—GRB 170817A (Goldstein et al. 2017; Savchenko et al. 2017; Pozanenko et al. 2018) that accompanied the first event GW 170817 detected from a BNS merger (Abbott et al. 2017a, 2017b). This is entirely consistent with theoretical expectations—no efficient mechanism for the formation of an electromagnetic pulse during a BBH merger has been proposed to date, and, besides, the probability to detect the emission from NSBH events is estimated to be very low (see, e.g., Postnov et al. 2019). GRB 170817A was observed with a delay of ≈1.7 s relative to the detection time $T_0$ of the GW event, i.e., the gamma-ray emission was formed already after the BNS merger. This is also consistent with expectations. The kilonova AT2017gfo was detected in the galaxy NGC 4993, in the burst arrival direction (Coulter et al. 2017; Evans et al. 2017; Troja et al. 2017). Its observations have allowed us to establish this unusual type of supernovae to be studied in detail for the first time.

The search for electromagnetic radiation from GW events is carried out primarily in the hard X-ray or soft gamma-ray range as well as in the optical one. The appearance of hard radiation in the form of a short GRB due to a BNS (and NSBH) merger was predicted by Blinnikov et al. (1984) and Paczynski (1991). The present-day all-sky hard X-ray monitors are able to successfully detect such bursts even at distances of tens of Gpc. The burst detection is extremely important, because it allows the localization region of the GW event determined by the method of triangulation of the signals measured by the LIGO detectors L1 and L2 located in USA and the Virgo detector V1 located in Italy to be noticeably reduced. In the O3 cycle of operation of the gravitational antennas the minimum and maximum event localization regions was 23 and more than 24 thousand sq. deg., respectively.

The optical transient associated with the appearance of a kilonova or a GRB afterglow is searched for in the optical range. The direct search for optical transients in such large localization regions is a very challenging problem. Nevertheless, many observatories and network projects are involved in solving the problem. Two tactics are used: (1) wide-angle telescopes carry out a mosaic scanning of the entire localization region, (2) narrow-angle ones successively observe the galaxies located in the three-dimensional localization volume determined by the solid angle and the range of possible distances to the source. The number of galaxies in such a volume can reach tens of thousands; nevertheless, their successive viewing turns out to be more efficient than the scanning of the entire region. Unfortunately, the existing catalogs of galaxies are not complete, and one cannot always restrict oneself only to tactic 2 when searching for an optical counterpart of a specific GW event.

Given the importance of the timely detection of the GRB accompanying a BNS or NSBH merger, we have initiated works within the program of searching for a transient hard X-ray emission from all such events recorded by the LIGO and Virgo detectors at the Space Research Institute of the Russian Academy of Sciences. The publicly accessible data from the SPI-ACS and IBIS-ISGRI gamma-ray telescopes of the INTEGRAL astrophysical observatory were used for our search. For the event S190425z (the second recorded BNS merger) such an emission has been found (Minaev et al. 2019; Chełovek et al. 2019a; see also Martin-Carillo et al. 2019; Savchenko et al. 2019).

In this paper we describe in detail the results of these observations, compare the GRB found with GRB 170817A that accompanied the first BNS merger event, and advance all the available arguments for the reliability of its detection.

**INSTRUMENTS AND METHODS**

As has already been said, this study is based on the observations of two main instruments onboard the INTEGRAL international astrophysical gamma-ray observatory (Winkler et al. 2003): the IBIS-ISGRI gamma-ray telescope (Lebrun et al. 2003; Ubertini et al. 2003) and the SPI gamma-ray spectrometer (Vedrenne et al. 2003; Roques et al. 2003). The principle of a coded aperture is used in both telescopes for imaging the sky and investigating the properties of individual cosmic sources.

The IBIS gamma-ray telescope is designed to map the sky in the hard X-ray and soft gamma-ray ranges and to study the detected sources with a rough energy resolution $E/\Delta E \sim 13$ at 100 keV. The telescope has a $30^\circ \times 30^\circ$ field of view (FWZ) at an angular resolution of 12′ (FWHM). The positions of bright bursts can be determined with an accuracy $\lesssim2′$. The sensitivity of the ISGRI detector of the telescope, which is an array of 16384 CdTe elements, is at a maximum in the range 18–200 keV. Its total area is 2620 cm$^2$, the effective area for events at the center of the field of view is $\sim1100$ cm$^2$ (half is blocked by the opaque mask elements).
The SPI gamma-ray spectrometer is designed for fine ($E/\Delta E \sim 550$ at 1.7 MeV) gamma-ray spectroscopy of the cosmic annihilation radiation (from the central regions of the Galaxy) and the radiation in nuclear gamma-ray lines of a radioactive origin (from the remnants of young nearby supernovae). The telescope has a maximum sensitivity in the range 0.05–8 MeV, a hexagonal field of view with a diameter of 32° (FWZI), and an angular resolution of 2.5° (FWHM); the geometrical area of 19 cryogenic superpure Ge detectors is $\approx 500$ cm$^2$.

For the timely detection of GRBs and other transient events that fell within the field of view of the IBIS and SPI telescopes and for the prompt notification of them via electronic GCN (Gamma-ray Coordinates Network) circulars, the IBAS automatic software system was developed (Mereghetti et al. 2003) and is successfully used. Bursts can also be detected independently, while analyzing the received or even archival data of the telescopes. GRBs that were not recorded by the IBAS system for various reasons were found in this way (Grebenev and Chelovekov 2007; Minaev et al. 2012, 2014; Chelovekov et al. 2019b). Such data can be analyzed using the standard INTEGRAL data processing software package — OSA (Courvoisier et al. 2003). In this paper we used the version 10.2 of the OSA package.

ACS of the SPI Gamma-Ray Spectrometer

Although some GRBs are successfully detected by the SPI gamma-ray spectrometer and the IBIS-ISGRI gamma-ray telescope inside (see, e.g., Mereghetti et al. 2003; Foley et al. 2008, 2009; Vianello et al. 2009; Minaev et al. 2014) and outside (see, e.g., Minaev et al. 2014; Chelovekov et al. 2019b) their fields of view, a considerably larger number of them are recorded by the anti-coincidence shield (ACS) of the SPI spectrometer with a much larger area (Rau et al. 2004, 2005). SPI-ACS is one of the most sensitive omnidirectional detectors in the entire history of GRB observations. Owing to the highly elliptical orbit of the INTEGRAL satellite (Eismont et al. 2003) with a period of 72 hours (64.8 hours after 2015), there are almost no zones of occultation by the Earth ($\gtrsim 80\%$ sky coverage) for it, while a stable background on a time scale of hundreds or even thousands of seconds allows a sub-threshold search for transients of various durations to be carried out. SPI-ACS has been successfully used in searching for transient gamma-ray emission from the GW event GW 170817 (Savchenko et al. 2017c; Pozanenko et al. 2018), having confirmed the detection of GRB 170817A by the Fermi/GBM monitor (Goldstein et al. 2017). We will also begin this study with an analysis of the SPI-ACS data.

SPI-ACS consists of 91 scintillation $\text{Bi}_2\text{Ge}_3\text{O}_12$ (BGO) crystals with a total mass of 512 kg (von Kienlin et al. 2003a, 2003b; Ryde et al. 2003). Their total effective area for the detection of GRBs reaches $\sim 0.7$ m$^2$. The total count rate is transmitted to the Earth with a resolution of 50 ms, the telemetry contains no spatial or spectral information. The energy range is known inaccurately, because the photomultiplier parameters and the crystal light outputs slightly differ and are not known exactly. The lower and upper thresholds can be roughly estimated to be $\sim 80$ keV and $\gtrsim 10$ MeV, respectively. Due to the peculiarities of the SPI design geometry, its shield, being almost omnidirectional, is insensitive to the bursts coming at small angles to the telescope axis.

**GRB Searching Technique**

The SPI-ACS data are the photon count rate history in one wide energy channel. However, one can fit the mean count rate, estimate and subtract the background, search for GRBs from these data, and analyze their significance using various techniques (see, e.g., Mereghetti et al. 2003; Savchenko et al. 2012, 2017a; Minaev et al. 2014; Minaev and Pozanenko, 2017). Slightly different results can be obtained when using different techniques. As we will see below, an important factor affecting the results is the choice of an appropriate time scale for our analysis (the time bin size in the light curve being studied).

When searching for short transient bursts associated with LIGO/Virgo GW events in the SPI-ACS data, we used the following technique. First, in the time intervals ($T_0 - 200$ s, $T_0 - 30$ s) and ($T_0 + 30$ s, $T_0 + 200$ s) equidistant from the GW signal arrival time $T_0$, the count rate was fitted by first- and second-order polynomial models using the SPI-ACS data with an original resolution of 50 ms. The model with the best residual was taken as a background model. The sample variance of the count rate was calculated relative to this model. Note that the sample variance of the SPI-ACS data differs from the Poissonian one by a factor of $1.2-1.6$ (von Kienlin et al. 2003a; Ryde et al. 2003; Rau et al. 2004, 2005). The adopted background model was extrapolated to the time interval ($T_0 - 30$ s, $T_0 + 30$ s), where we searched for significant excesses of the count rate above the background. We used time series with various step (bin) lengths, from 0.1 to 10 s (naturally, a multiple of the bin length of the original time series...
The significance of the detected excess of the count rate in some bin above the background count rate was estimated using the sample variance reduced to the selected bin size. The algorithm is optimal for searching for a pulsed signal whose duration roughly matches the bin length chosen for our search (from 0.1 to 10 s).

The search for short GRBs in the SPI data is described in detail in Minaev et al. (2014); the search for bursts in the IBIS-1S GRI data is described in Chelovekov et al. (2019b). In our paper, this technique as applied to the search for a burst of hard X-ray and soft gamma-ray emission accompanying a GW signal differed only by the choice of a smaller step for the analyzed time series. We took the same set of steps that was used to construct the light curves from the SPI-ACS data.

EVENT S190425Z

The GW event S190425z was recorded by the LIGO/Virgo detectors on April 25, 2019, at 08h18m05s017 UTC. It was assigned with a significance >99% to the events caused by a BNS merger (Singer 2019a), having become the second detected BNS merger in the entire history of observations. The false alarm rate (FAR) of such events was estimated to be very low, FAR = 4.5 × 10^{-13} s^{-1} or 1 event in 69834 years.2

Only two detectors of the GW interferometer were operating at the detection time: LIGO L1 (Livingston, USA) and Virgo V1 (Italy). Accordingly, the event localization was much more uncertain than that in the case of GW 170817 (Abbott et al. 2017a). The area of the 50 and 90% localization regions was 1378 and 7461 sq. deg., respectively (Singer 2019a). The region was divided into two parts of close sizes—northern and southern (see Fig. 5 below). The source turned out to be a factor of 4 farther than GW 170817, it was at a distance of 156 ± 41 Mpc. This further complicated the search for its manifestations in all ranges of the electromagnetic spectrum. The characteristics of the event S190425z are given in Table 1. For comparison, similar data on the event GW 170817 can be found there.

Immediately after the announcement of the event S190425z and its identification (Singer 2019a), optical, soft X-ray, and radio telescopes worldwide were involved in searching for a possible afterglow of this object or a kilonova that could have flared up at the BNS merger location (see, e.g., Abbott et al. 2017b). Some of the first results of this study were presented in Coughlin et al. (2019) and Hosseinzadeh et al. (2019). Although it is already clear that the corresponding event was not quickly detected in these energy ranges, there is no doubt that these are only the first ones in the flow of works based on the results of such studies.

RESULTS

As the upper panel of Fig. 1 shows and as was first reported by Martin-Carilla et al. (2019) and Minaev et al. (2019a), the SPI-ACS detector onboard INTEGRAL recorded a significant excess of the photon count rate above the background ∼5.94 s after the time T_0 of the event S190425z (Singer 2019a). The bin size in the count rate history in this figure is 0.85 s. The a priori detection significance (the signal-to-noise ratio corrected for the non-Poissonian nature of the SPI-ACS count rate) is S/N ≃ 4.4 standard deviations (Table 2). It is clearly seen from the figure that the excess is indeed significant—in a time interval of 500 s with the center at T_0 there is no spike even at 3σ (the level indicated by the dashed red line) except the named one.

The bottom panel of the figure shows a similar photon count rate history near the event GRB 170817A. There are no significant excesses of the count rate on it. This is because the duration of the GRB detected in the SPI-ACS data from this event was much smaller (∼0.1 s; Savchenko et al. 2017c; Pozanenko et al. 2018) than the chosen bin size. If we consider the count rate history with a smaller bin, 0.15 s (see the bottom panel of Fig. 2), then a significant (S/N ≃ 4.3) spike corresponding to GRB 170817A appears. When reducing the bin size to 0.1 s, its significance reaches a maximum of S/N ≃ 4.6 (Table 1).

Amazingly, another significant (with S/N ≃ 3.6) spike appears ∼0.5 s after the time T_0 on the upper panel of Fig. 2 in the count rate recorded with a 0.15 s step near the GW event S190425z (Minaev et al. 2019). The total duration of this spike reaches ∼0.5 s, although the emission maximum is contained in a very narrow (∼0.15 s) peak. The significance of the second spike on this light curve decreased noticeably (to S/N ≃ 3.1 in one bin). This is not surprising for such a fine division of the time series, because the actual duration of the second spike reaches ∼1.3 s.

Thus, two significant excesses above the background level were found in the ±30 s interval near T_0 for this event (Fig. 2, the upper panel). In what follows, we will call them the first and second pulses in the time profile of this GRB, which, thus, has a total duration of ∼6.0 s. The total significance of the double event is S/N ≃ 5.5 (see Table 1). The estimate of the fluence from such a burst given in the table, with a mean value of F_m ≃ 4.4 × 10^{-7} erg cm^{-2} in the range

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2 gracedb.ligo.org/superevents/S190425z.
Table 1. Basic parameters of the GW events GW 170817 and S190425z and GRB 170817A and GRB 190425 accompanying them

| LIGO/Virgo event | S190425z   | GW 170817   |
|------------------|------------|-------------|
| Trigger time \(T_0\)^a | 2019-04-25 08:18:05 | 2017-08-17 12:41:04 |
| Distance to the source, Mpc | 156 ± 41 | 40 ± 8 |
| Localization region\(^b\), 90% | 7461 | 16 |
| Angle to the SPI-ACS detector axis | 26° – 60° | 105° |

| GRB              | GRB 190425 | GRB 170817A |
|------------------|------------|-------------|
| Pulse in the event profile | first + second | first | first + second |
| Experiment       | SPI-ACS    | SPI-ACS    | Fermi/GBM\(^c\) |
| Beginning of the event\(^d\), s | 0.44 | 2.0 | 1.7 |
| Total duration\(^d\), s | 6.0 | 0.1 | 4.1 |
| Integrated number of counts | 2300 ± 420 | 570 ± 120 | – |
| Significance \((S/N)\), \(\sigma\) | 5.5 | 4.6 | 8.7 |
| Probability\(^e\) | \(1.9 \times 10^{-8}\) | \(2.1 \times 10^{-6}\) | \(1.7 \times 10^{-18}\) |
| FAR\(^f\), events/s | \(6.4 \times 10^{-5}\) | \(4.2 \times 10^{-4}\) | – |
| Joint probability\(^g\) | \(1.6 \times 10^{-4}\) | \(4.8 \times 10^{-3}\) | – |
| Fluence \(F\)^h, erg cm\(^{-2}\) | \(8.0 \times 10^{-8} – 2.4 \times 10^{-6}\) | \(1.7 \times 10^{-8} – 5.2 \times 10^{-7}\) | \((2.1 \pm 0.3) \times 10^{-7}\) |
| Energy release \(E_{\text{iso}}\)^i, erg | \(2.2 \times 10^{47} – 6.7 \times 10^{48}\) | \(3.8 \times 10^{45} – 1.2 \times 10^{47}\) | \((4.7 \pm 0.7) \times 10^{46}\) |

\(^a\) The LIGO/Virgo event detection time, UTC.
\(^b\) The area of the event localization region, sq. deg.
\(^c\) According to Goldstein et al. (2017) and Pozanenko et al. (2018).
\(^d\) The beginning (from \(T_0\)) and total duration of the GRB, s.
\(^e\) The probability of a chance spike under the assumption of Gaussian statistics for \(S/N\).
\(^f\) The false alarm rate of random events with such a temporal structure (from the data of the entire revolution).
\(^g\) The probability that takes into account the identification with the GW event by chance and the enumeration of time series with different bin sizes (Blackburn et al. 2015; \(T_{\text{min}} = 0.1\) s, \(T_{\text{max}} = 30\) s).
\(^h\) The equivalent fluence in the range 10–1000 keV, erg cm\(^{-2}\).
\(^i\) The equivalent isotropic energy radiated during the burst, erg.

10–1000 keV, was obtained by taking into account the normalization of the SPI-ACS counts based on the fluences measured by the Fermi/GBM monitor for a number of short GRBs simultaneously detected by both instruments (see the Appendix). It will be discussed in more detail below.

Each of the pulses reaches a maximum significance on the light curve with its specific bin size: 0.15 and 0.85 s for the first and second pulses, respectively. Both pulses have an equally high significance \(S/N \approx 3.5\) and 3.3 standard deviations on the light curve with a 0.25-s bin size. The joint probability that, apart
Table 2. Comparison of the parameters of the GRBs associated with the NS merger events GW 170817 and S190425z from the SPI-ACS experimental data

| Event                                | GRB 190425 | GRB 170817A |
|--------------------------------------|------------|-------------|
| Pulse in the event profile           | First      | Second      |
| Beginning of the pulse $T_i^a$, s    | 0.44       | 5.54        | 2.00        |
| Time of the maximum count rate $T_m^a$, s | 0.54     | 5.94        | 2.05        |
| Binning $N_t^b$                       | 5          | 17          | 2           |
| Duration $\Delta T_i^c$, s           | 0.25       | 0.85        | 0.10        |
| Integrated number of counts $C_i$ in pulse $i$ | 700 ± 200 | 1600 ± 370  | 570 ± 120   |
| Significance ($S/N$), $\sigma$       | 3.5        | 4.4         | 4.6         |
| Probability$^d$                       | $2.3 \times 10^{-4}$ | $5.4 \times 10^{-6}$ | $2.1 \times 10^{-6}$ |
| FAR, events/s$^e$                     | $1.4 \times 10^{-3}$ | $2.7 \times 10^{-5}$ | $4.2 \times 10^{-4}$ |
| Conservative probability$^f$         | $3.5 \times 10^{-3}$ | $8.5 \times 10^{-4}$ | $4.8 \times 10^{-3}$ |

$^a$ The beginning of pulse $i$ and its maximum (from the GW event time $T_0$), s.
$^b$ The optimal binning with respect to the original time series with a 50 ms bin.
$^c$ The corresponding optimal bin length $\Delta T_i = 0.05 N_t$ s (characterizes the pulse duration).
$^d$ The probability under the assumption of Gaussian statistics for $S/N$.
$^e$ The false alarm rate of such random events (from the data of the entire revolution).
$^f$ The probability that takes into account the association with the GW event by chance and the enumeration of time series with different bin sizes (Blackburn et al. 2015, $T_{min} = 0.1$ s, $T_{max} = 30$ s).

from the statistical significance of the pulses, takes into account the probability of a chance association with the event S190425z (as well as the increase in the number of trials due to the selection of an optimal bin size) will be calculated below precisely for such a light curve. Basic parameters of both burst pulses are given in Table 2.

Similar parameters for GRB 170817A from the SPI-ACS data are also given there for comparison. According to the light curve in Fig. 2, this burst seems to contain only one rather narrow pulse. In fact, as was noted in Pozanenko et al. (2018), the SPI-ACS detector recorded only its initial hard part. According to the Fermi/GBM data (Goldstein et al. 2017), GRB 170817A had a much more extended profile in the X-ray range 8–50 keV with a total duration of $\sim 4.1$ s. This is clearly seen from Fig. 3, where the light curves near this event recorded by the Fermi/GBM (red and blue histograms) are shown in comparison with the light curve recorded by the SPI-ACS detector (black histogram). In the range 50–300 keV of this instrument, which is close to the SPI-ACS range (> 80 keV), the narrow initial gamma-ray pulse dominates in the burst profile, but there is also an indication of the presence of a weak second pulse with a duration of $\sim 1$ s $\sim 5.3$ s after the NS merger. Thus, the GRBs that accompanied both nearby recorded GW events have comparable durations and the same two-component structure of the time profile.

Note that there is no extended emission that could be taken as an afterglow in the SPI-ACS light curve up until 250 s after $T_0$ (see Fig. 1). The extended emission was not recorded in the light curve of GRB 170817A either (Pozanenko et al. 2018). No gamma-ray emission that could be associated with the GW event was recorded in the SPI telescope itself either. However, the detection of emission by SPI-ACS implies that the gamma-ray photons arrived at a large angle to the telescope axis and could not be recorded in its field of view.
Fig. 1. (Color online) Time dependence of the SPI-ACS photon count rate immediately before and after (±250 s) the GW events S190425z (top) and GW 170817 (bottom). The bin length is 0.85 s, the time is measured from the LIGO/Virgo event detection time (vertical dashed line), the background was subtracted according to the model. The dashed (red) lines mark the range of random deviations at the 3σ level.

**Estimation of the Event Significance**

To estimate the probability that the two pulses on the hard X-ray light curve immediately after the detection time $T_0$ of the event S190425z appeared by chance, we used a two-parameter formula for calculating the probability (Blackburn et al. 2015, 2019), which, apart from the statistical significance of the pulses, takes into account the probability of their chance association with the event S190425z, i.e. their appearance in a certain time interval after the event. The formula also takes into account the increase in the probability to find a significant random pulse due to the selection of an optimal time step for the count rate history, simply through the increase in the number of trials. This formula was first applied when estimating the significance of the weak transient GRB recorded by Fermi/GBM shortly after the first LIGO/Virgo GW event GW 150914 (Connaughton et al. 2016).

The estimation is performed in several stages. First, the false alarm rate (FAR), the empirically determined rate of occurrence of random events (pulses) on the light curve with a significance equal to or greater than a certain value, is calculated. Then, the probability for such an event to occur no later than a time $dT$ after $T_0$ is calculated. The probability estimate does not depend directly on the step (bin) of the light curve on which the events (pulses) were searched for. Let us estimate the rate of occurrence of a complex of two pulses with parameters corresponding to GRB 190425 (Tables 1 and 2). For this purpose, we will use the SPI-ACS data obtained over the entire revolution of the INTEGRAL observatory in which the burst was recorded (rev. 2083). We will
investigate the count rate history with a 0.25-s step (i.e., the time series consists of 591200 bins). A total of 8 such complexes were found in 125 ks in the count rate history with a separation between the beginnings of the pulses less than 5.5 s. The short pulse preceded the longer one for 5 of them and lagged behind for the remaining ones. Thus,

\[
\text{FAR} \approx \frac{8}{1.25 \times 10^5 \text{s}} = 6.4 \times 10^{-5} \text{s}^{-1}.
\]

The joint, very conservative (overevaluated) estimate of the occurrence probability of a random spike coincident in time (Blackburn et al. 2015; Connaughton et al. 2016) is written as

\[
P = \text{FAR} \times \ln((1 + T_{\text{max}}/T_{\text{min}})dT,
\]

where \(dT\) is the duration of the time interval from \(T_0\) to the beginning of the first pulse; \(T_{\text{max}}\) is the duration of the interval of the time series after \(T_0\) on which the events were searched for; \(T_{\text{min}}\) is the duration of the minimum measurable match. Conservatively, \(T_{\text{max}}\) can be limited to 30 s; \(T_{\text{min}}\) is, obviously, the minimum bin length of the time series for which the pulses were searched for, it is 0.1 s in our study (see also Connaughton et al. 2016). Substituting these values, we obtain the following probability estimate:

\[
P = 6.4 \times 10^{-5} \ln\left(1 + \frac{30}{0.1}\right) \times 0.44 \approx 1.6 \times 10^{-4}.
\]

This estimate reflects the probability of random occurrence of a complex of two pulses with a given intensity at a distance of 0.44 s after the GW event S190425z.
The same estimate can be obtained separately for each of the recorded pulses. The results are given in Table 2. Note that 198 positive and 139 negative spikes exceeding $S/N = 3.5$ were found on the light curve with a bin size of 0.25 s (a total of 591,200 bins, the curve for the entire evolution). The number of negative spikes corresponds to the expected one for Gaussian statistics with $P(|\geq 3.5\sigma|) \approx 2.3 \times 10^{-4}$, the number of positive ones exceeds it by 40%. This is most likely due to the presence of a noticeable number of high-intensity pulses associated with charged particles in the SPI-ACS count rate. They give only positive spikes. In this case, the spikes with a low significance ($S/N > 3$) are consistent with the Gaussian probability. Clearly, under such conditions the empirical estimates (see Table 2) should be used to determine the detection probability of a random spike.

Four positive (including the second pulse of GRB 190425) and one negative spikes with $S/N = 4.4$ or exceeding it were detected on the light curve with a bin size of 0.85 s (containing 173,900 bins). For Gaussian statistics we should have recorded 65 positive spikes with $S/N > 4.6$ and 3 negative ones were recorded over the entire revolution of the INTEGRAL observatory corresponding to this GRB (rev. 1851), which had a duration of 155 ks (1,549,000 bins). For Gaussian statistics the probability to record such a pulse by chance is $2.1 \times 10^{-6}$, i.e., 3 positive spikes should have been recorded in 155 ks. The false pulses associated with charged particles dramatically worsen the statistics. According to the measured number of false bursts, FAR $= 4.2 \times 10^{-4}$ s$^{-1}$ for this event (Table 2).

A conservative estimate of the probability of a chance coincidence for this event made by the method of two-parameter analysis (Blackburn et al. 2015; Connaughton et al. 2016) gives

$$P = 4.2 \times 10^{-4} \ln \left(1 + \frac{30}{0.1}\right) \times 2.0 \approx 4.8 \times 10^{-3}.$$ 

The estimate does not allow the random origin of the event to be excluded. However, the significance of GRB 170817A was confirmed independently—by its simultaneous detection by the Fermi/GBM monitor with a much higher significance $S/N \approx 8.7$ (Table 1).

**Comparison with the Significance of GRB 170817A**

For comparison with the estimate of the significance of GRB 190425, let us perform a similar analysis of the data for the first GRB 170817A accompanying the BNS merger event GW 170817 recorded by the SPI-ACS detector. Recall that the maximum detection significance of this burst was $S/N \approx 4.6$ on the light curve with a bin size of 0.1 s (Table 1).

In the detector count rate history with such a bin size, 65 positive spikes with $S/N > 4.6$ and 3 negative ones were recorded over the entire evolution of the INTEGRAL observatory corresponding to this GRB (rev. 1851), which had a duration of 155 ks (1,549,000 bins). For Gaussian statistics the probability to record such a pulse by chance is $2.1 \times 10^{-6}$, i.e., 3 positive spikes should have been recorded in 155 ks. The false pulses associated with charged particles dramatically worsen the statistics. According to the measured number of false bursts, FAR $= 4.2 \times 10^{-4}$ s$^{-1}$ for this event (Table 2).

**IBIS-ISGRI Observations**

Figure 4 shows the time dependence of the photon count rate recorded by the ISGRI detector of a different telescope onboard the INTEGRAL observatory.
IBIS, near the event S190425z. The upper and lower panels of the figure correspond to a different choice of the time step length for these curves, 0.15 and 0.85 s, respectively. The data were taken in the energy range 30–100 keV. We see that from \( T_0 - 20 \) s to \( T_0 + 50 \) s no significant bursts of radiation that could be interpreted as an extension of GRB 190425 to the hard X-ray range were detected in the count rate history. No bursts of radiation were detected on a longer time scale either (see Chelovekov et al. 2019a; Savchenko et al. 2019).

Of course, we could not expect the GRB detected by SPI-ACS to be recorded in the field of view of the telescope. However, as was recently shown by Chelovekov et al. (2019b), the IBIS-ISGRI telescope is able to successfully detect the bursts coming from the side, at large angles to its axis, and, therefore, some emission from GRB 190425 could be recorded. The upper limit (3σ) on the flux of any possible excess emission with a duration of \(~1\) s in the range 10–1000 keV is \(2.1 \times 10^{-6}\) erg cm\(^{-2}\) (if the IBIS-ISGRI data in the energy range 30–100 keV are used) and \(1.2 \times 10^{-6}\) erg cm\(^{-2}\) (if the data in the range 100–500 keV are used). To estimate the flux from the burst that presumably arrived at an angle of 26°–60° to the telescope axis, we used the normalization based on several hundred GRBs observed simultaneously by the Fermi/GBM and IBIS-ISGRI detectors (Chelovekov et al. 2019b). The inferred limit is consistent with the flux measured from the burst by SPI-ACS.

**Detection of S190425z in Other Experiments**

GRB 190425 from the LIGO/Virgo event S190425z was not detected in any other X-ray and gamma-ray experiments, including SWIFT/BAT (Sakamoto et al. 2019), MAXI/GSC (Sugizaki et al. 2019), WIND/KONUS (Svinkin et al. 2019), AGILE/MCAL (Casentini et al. 2019), Fermi/GBM (Fletcher 2019), and Insight-HXMT/HE (Xiao et al. 2019). However, for all these instruments, except Fermi/GBM, the flux recorded by SPI-ACS (see Table 1) was definitely below the detection threshold. The derived 3σ upper limits on the flux of pulsed emission with a duration of 1 s were, at best, comparable to the limits set by the IBIS-ISGRI telescope and more often exceeded it noticeably.

According to our analysis of a representative sample of short bursts recorded simultaneously by the Fermi/GBM and INTEGRAL/SPI-ACS detectors (see the Appendix and Fig. 7), a GRB with the characteristics of the event under consideration should have been necessarily recorded by Fermi/GBM. Nevertheless, this instrument did not record any burst within the ±30 s interval from the time \(T_0\) of the GW event; the 3σ limit on its fluence in the range 10–1000 keV was, depending on the spectral model used, \((0.9 - 8.4) \times 10^{-7}\) erg cm\(^{-2}\) for a very short (with a duration \(~0.1\) s) burst, \((0.3 - 2.5) \times 10^{-6}\) erg cm\(^{-2}\) for a typical short (\(~1\) s) burst, and \((0.9 - 7.7) \times 10^{-6}\) erg cm\(^{-2}\) for a long (\(~10\) s) burst (Fletcher 2019).
DISCUSSION

The Absence of Fermi/GBM Detection

The absence of detection of GRB 190425 by the Fermi/GBM monitor can be explained by the occultation of its source by the Earth. According to Fletcher (2019), the Fermi/GBM observations covered only 56% of the region of initial localization of the source by the LIGO/Virgo detectors.

Figure 5 presents a refined map of the LIGO/Virgo localization region for the event S190425z (Singer 2019b) and the region of occultation of the Fermi satellite by the Earth (unshaded). Indeed, almost the entire northern part of the GW signal localization region was occulted by the Earth at the GRB detection time. The curve of optimal burst detection by SPI-ACS (at an angle of 90° to the telescope axis) is indicated by the dashed line. The detector is sensitive to events in a wide band offset at least by ±75° from this curve; the entire zone of maximum probability from the northern localization region of S190425z falls into this band.

Thus, the intersection of the region of occultation of the Fermi satellite by the Earth with the LIGO/Virgo localization region of the event is the zone of probable location of the optical counterpart (a GRB afterglow or a kilonova) possibly accompanying the NS merger S190425z. The region in the IBIS-1SGrI field of view (the shaded trapezoidal region centered at R.A. ≈ 277°, Decl. ≈ 30°) where the burst would be definitely detected can also be excluded from this zone. The SPI field of view virtually coincides with the IBIS-1SGrI field of view.
Fig. 6. (Color online) Possible position of GRB 190425 accompanying the NS merger event S190425z recorded by the LIGO/Virgo detectors on the Amati (2002) diagram constructed by including only the short bursts (Minaev and Pozanenko 2019). The vertical dashed lines indicate the boundaries of the 2σ uncertainty region of $E_{\text{iso}}$ for GRB 190425. They were obtained from the SPI-ACS calibration (see the Appendix) by converting the fluence $F$ to $E_{\text{iso}}$ for a photometric distance of 156 Mpc ($E_{\text{iso, min}} = 2.2 \times 10^{47}$ erg and $E_{\text{iso, max}} = 6.7 \times 10^{48}$ erg). The intersection of these lines with the 2σ uncertainty region of the $E_p - E_{\text{iso}}$ relation gives the maximum possible values of $E_p$ (at the 2σ level): $E_{p, \text{min}} = 7$ keV and $E_{p, \text{max}} = 400$ keV. The blue dotted lines additionally limit $E_p$ under the assumption that the energy radiated during GRB 170817A and GRB 190425 was the same, while the differences in their observed manifestations were associated only with different orientations of the axes of the relativistic jet with respect to the observer.

**Similarities and Differences between GRB 190425 and GRB 170817A**

The characteristics of GRB 170817A and GRB 190425 detected in the SPI-ACS experiment are given in comparison in Tables 1 and 2.

GRB 190425 and GRB 170817A are similar in that they both consisted of two episodes—pulses: the first, short (in the case of GRB 170817A, only it was detected by SPI-ACS), and the second, longer ones. The second pulse lasted almost 4 s in the case of GRB 170817A and 1.3 s (with the maximum 5.4 s after the first pulse, see Table 2) in the case of GRB 190425. The total duration of both GRBs was comparable and equal to ~4–6 s. Extended pulses have been observed in the time profile of a number of other short GRBs (Gehrels et al. (2006) and references therein), effectively increasing their duration.

The second pulse of GRB 170817A was noticeably softer than the first one (see Fig. 3 and, in more detail, Pozanenko et al. (2018)). The second pulse of GRB 190425 remained fairly hard; that is why it was detected by SPI-ACS whose sensitivity threshold exceeds ~80 keV. If this pulse were as soft as the second pulse of GRB 170817A ($kT \sim 11$ keV), then SPI-ACS would be unable to detect it. Moreover, as was shown by Gottlieb et al. (2018) and Pozanenko et al. (2018), the second pulse in the time profile of GRB 170817A was most likely associated with the thermal heating of the shell at the jet breakout (the cocoon radiation). Since the distance to the GRB 190425 source (~156 Mpc) noticeably exceeds the distance to the GRB 170817A source (~40 Mpc, see Table 1), the intensity of the thermal component in the GRB 190425 spectrum should have been lower than the intensity of the thermal component in the
GRB 170817A spectrum by a factor of \((156/40)^2 \sim 15\); not only SPI-ACS, but even Fermi/GBM would be unable to detect it. It may well be that the second pulses in these two bursts had a different origin.

Given that the two pulses are spaced 5.4 s apart in the case of GRB 190425, a two-jet GRB scenario could be realized in it (Barkov and Pozanenko 2011), where the first short pulse corresponds to the jet formed by neutrino annihilation (Chen and Beloborodov 2007) and the second, longer one appears as a result of accretion from the formed accretion disk and the Blandford–Znajek effect (Blandford and Znajek 1977). In this case, the angle at which an observer sees the jet of GRB 190425 should be smaller than the angle of observation of the jet in GRB 170817A. Thus, the two observed episodes of radiation in the light curves of GRB 170817A and GRB 190425 can be different in nature.

**Classification and Spectral Properties**

There is no doubt that both GRBs belong to the class of type I bursts (also called short bursts), whose sources and progenitors are merging neutron stars. This follows from the LIGO/Virgo observations and data analysis.

Although the SPI-ACS detector has no spectral channels, some conclusions about the spectral properties of the gamma-ray emission from GRB 190425 can be given. For example, using the empirical “peak energy \(E_p\) in the energy spectrum \(\nu F_\nu\)–equivalent isotropic radiated gamma-ray energy \(E_{iso}\)” relation (Amati 2002) for type I GRBs (Minaev and Pozanenko 2019), we can set the limits within which the energy \(E_p(1+z)\) for GRB 190425 should lie (Fig. 6). The solid line in this figure indicates the best-fit de-
\[ E_p(1+z) \simeq 105 \left( \frac{E_{iso}}{10^{49} \text{erg}} \right)^{0.38\pm0.06} \text{keV}, \]

while the dashed (red) lines indicate the \( \pm 2\sigma \) burst scatter region relative to this dependence. The redshift of the burst source is \( z \simeq 0.0364 \ll 1 \) and, therefore, below we will neglect the factor \((1+z)\).

We will determine the energy \( E_{iso} \) based on our estimates of the minimum/maximum possible fluence from the burst reduced to the Fermi/GBM energy range 10–1000 keV. The estimates were obtained from the fluence measured by SPI-ACS (in counts, see Table 1) using the calibration of the ratio of the fluences from a number of short GRBs measured by Fermi/GBM and simultaneously by the SPI-ACS detector (see the Appendix and Fig 7). The boundary values of the fluence were then converted to \( E_{iso} \) by taking into account the photometric distance to the source of 156 Mpc. The derived limits \( E_{iso,\text{min}} = 2.2 \times 10^{47} \text{erg} \) and \( E_{iso,\text{max}} = 6.7 \times 10^{48} \text{erg} \) are indicated in Fig. 6 by the vertical dashed lines. Their intersection with the \( 2\sigma \) burst scatter region relative to the \( E_p - E_{iso} \) relation gives the maximum possible values of \( E_p \) at the \( 2\sigma \) significance level: \( E_{p,\text{min}} = 7 \) and \( E_{p,\text{max}} = 400 \text{ keV} \) (correspond to the lower and upper corners of the zone of intersection of the uncertainty bands in Fig. 6).

If the \( E_p - E_{iso} \) relation is assumed to be associated with the geometry of the GRB source observations, namely with the angle between the axis of the relativistic jet and the direction to the observer (Eichler and Levinson 2004; Levinson and Eichler 2005; Ito et al. 2015, 2019), then additional constraints on \( E_p \) can be obtained.

Indeed, suppose that the total energy radiated in the gamma-ray range during GRB 170817A and GRB 190425 was approximately the same. Then, the angle \( \theta \) between the jet axis and the direction to the observer in the GRB 190425 source should be smaller than that in the GRB 170817A source (see Song et al. 2019), because \( E_{iso} \) for GRB 190425 exceeds \( E_{iso} \) for GRB 170817A by many times (see Fig. 6). The decrease in the possible values of the angle \( \theta \) with increasing \( E_{iso} \) is also confirmed by detailed calculations within the jet model with a Gaussian profile (Zhang and Meszaros 2002; Troja et al. 2018). Conservatively, \( E_p \) can be constrained from below by \( E_{p,\text{min}} = 70 \text{ keV} \), because for the presence of a general positive correlation, it is necessary that \( E_p \sim E_{iso}^{\alpha} \), where \( \alpha > 0 \) (the lower dotted blue line in the figure). The upper limit \( E_{p,\text{max}} = 400 \text{ keV} \) will remain the same, it is constrained by the uncertainty of the observed \( E_p - E_{iso} \) relation (upper dotted line).

The derived limits are consistent with the detection of GRB 190425 by SPI-ACS at energies above 80 keV.

**CONCLUSIONS**

The report by Minaev et al. (2019) on the detection of a possible GRB in the time interval 0.5–6.0 s after the GW event S190425z by the SPI-ACS detector of the INTEGRAL observatory remained virtually unnoticed. The absence of detection of this burst by the Fermi/GBM monitor and, possibly, an insufficiently serious assessment of the reality of the burst by Martin-Carillo et al. (2019) and Savchenko et al. (2019) based on an analysis of the same SPI-ACS data had an effect. In this paper we confirmed the sufficiently high statistical significance of the burst, explained the absence of its detection by Fermi/GBM, and advanced a number of additional arguments for its existence.

1. GRB 190425 was recorded by the SPI-ACS detector 0.44 s after the detection of the GW event S190425z. The burst consisted of two emission pulses (episodes) 0.25 and 0.85 s in duration (the second pulse began 5.1 s after the first one). The burst had a total duration \( \sim 6.0 \text{ s} \) and a time profile largely similar to those of GRB 170817A accompanying the first BNS merger event GW 170817 recorded by LIGO/Virgo.

2. The joint probability of random occurrence of the complex consisting of the two pulses described above is \( 1.6 \times 10^{-4} \). Apart from the usual significance \( S/N \simeq 5.5\sigma \) of the double burst, this probability takes into account the possibility of its erroneous association with the event S190425z and the increase in the number of trials when selecting an optimal time scale (Blackburn et al. 2015). For comparison, the probability of detecting GRB 170817A with a duration of 0.1 s and a significance \( S/N \simeq 4.6\sigma \) \( \sim 2.0 \text{ s} \) after the event GW 170817 by SPI-ACS is \( 4.8 \times 10^{-3} \).

3. Both sources of the detected bursts, GRB 170817A and GRB 190425, are at distances (40 and 156 Mpc, respectively) much smaller than the distances to other BNS (as well as BBH and NSBH) merger events recorded in the LIGO and LIGO/Virgo O2 and O3 cycles of observations.
4. No significant evidence for the presence of gamma-ray emission was revealed in any of the individual BBH or NSBH merger events recorded by the LIGO/Virgo detectors (Savchenko et al. 2016, 2017b, 2018).

5. Our conservative estimate of the isotropic energy $E_{\text{iso}}$ radiated during GRB 190425 is bounded by the $2\sigma$ range from $2.2 \times 10^{47}$ to $6.8 \times 10^{48}$ erg, which exceeds the estimate of $E_{\text{iso}}$ for GRB 170817A at least by a factor of 5. The estimate of the peak energy $E_p$ in the spectrum of GRB 190425 is bounded by the $2\sigma$ range from 70 to 400 keV (Fig. 6).

6. Since $E_{\text{iso}}$ for GRB 190425 exceeds $E_{\text{iso}}$ for GRB 170817A by many times, the angle between the direction to the observer and the jet axis in GRB 190425 should have been smaller than that in GRB 170817A (see, e.g., Song et al. 2019). This is obvious under the assumption that the same radiated energy of the bursts and is confirmed by the computations within the model of a Gaussian jet profile (Zhang and Meszaros 2002; Troja et al. 2018). The estimate of the angle to the jet axis serves as an independent estimate of the angle between the direction to the observer and the orbital plane of the binary system of merging neutron stars, which is poorly determined directly from GW observations (under the assumption that the jet axis is perpendicular to the orbital plane of the binary).

7. The absence of detection of GRB 190425 by the Fermi/GBM monitor (one of the most sensitive omnidirectional GRB experiments in the range above 10 keV) can be explained by the fact that its source was in the Earth’s shadow at the burst time.

8. As a result of the overlap between the LIGO/Virgo localization region of the event S190425z and the region shadowed for Fermi/GBM by the Earth during GRB 190425, the possible localization region of the event is significantly reduced (compared to the original LIGO/Virgo localization region) and consists only of its northern part (Fig. 5).

9. Apart from the large size of the event localization region (7461 sq. deg.), the absence of detection of an optical counterpart of the event in the form of an afterglow may be associated with a noticeable deflection of the jet axis from the direction to the observer, which leads to an exponential suppression of the flux being recorded. The fairly large (156 Mpc) distance to the source does not allow the possible volume of its localization to be effectively studied. The targeted observations of galaxies in this volume are complicated by incompleteness of existing catalogs of galaxies, while the survey observations do not provide a sensitivity need to record the transient. So, the intensive follow-up observations aimed at finding the kilonova (for example, the ZTF and Palomar Gattini-FR telescopes viewed ~20% of the event localization region (Coughlin et al. 2019), while the MMT and SOAR telescopes viewed 40% of the possible localization volume (Hosseinzadeh et al. 2019) were unsuccessful, perhaps for precisely these reasons.

To continue the search for an optical counterpart of the event S190425z, it is necessary to concentrate on its localization region in the northern hemisphere refined in this paper and to study more carefully the optical transients discovered in it.

**APPENDIX**

**CALIBRATION OF THE FLUX FROM SHORT BURSTS IN THE SPI-ACS DETECTOR**

To estimate the fluence corresponding to the counts recorded by the SPI-ACS detector during GRB 190425, we selected and investigated a representative sample of short GRBs observed simultaneously by the INTEGRAL/SPI-ACS detector and the Fermi/GBM monitor. As a result, we established a correspondence between the fluences measured by these instruments (in counts and erg cm$^{-2}$, respectively).

The events recorded from July 14, 2008, to June 30, 2019, with at least one spike above the mean count rate exceeding the $3\sigma$ significance level present in the interval $T_{90}$ on the SPI-ACS light constructed with a 50-ms step were selected into the sample from the Fermi/GBM catalog$^4$ (Bhat et al. 2016). Given the origin of GRB 170817A and GRB 190425 discussed in the paper and their actually measured durations, we left in the sample only the bursts for which the interval $T_{90}$ determined from the GBM data was less than 6 s.

$^3$The time interval between the times of accumulation of 5% and 95% of the integrated number of counts by the GBM monitor (Koshut et al. 1996).

$^4$The continuously updated burst catalog of this monitor can be found at heasarc.gsfc.nasa.gov/W3Browse/fermi/termigbrst.html.
For all of the 278 bursts of the sample selected in this way, the SPI-ACS background photon count rate was fitted by a cubic polynomial in the intervals \((T_0 - 300 \, \text{s}, T_0 - 50 \, \text{s})\) and \((T_0 + 200 \, \text{s}, T_0 + 500 \, \text{s})\) separately in each interval; the burst start time \(T_0\) was taken from the GBM catalog. The mean value of two model count rates at the boundaries of the interval \((T_0 - 50 \, \text{s}, T_0 + 200 \, \text{s})\) was used as the background count rate \(B\) in this interval. The integrated number of counts recorded during the burst was calculated as the total excess of the count rate above \(B\) in the time interval \(T_{100}\). Only the bursts with \(C\) determined with a significance exceeding 3 standard deviations were left for the subsequent analysis.

In Fig. 7 the fluences \(F\) (in erg cm\(^{-2}\)) recorded by the Fermi/GBM monitor during the remaining bursts are given as a function of the integrated number of counts \(C\) recorded from these bursts by the SPI-ACS detector. This dependence can be fitted by a model power law:

\[
F_{\text{in}} = 2.19 \times 10^{-6} \left( \frac{C}{10^4 \, \text{counts}} \right)^{1.10 \pm 0.06} \text{erg cm}^{-2},
\]

indicated in Fig. 7 by the solid line. The dotted lines indicate the \(\pm 2\sigma\) scatter band of the actually measured fluences from the GRBs relative to this straight line. Previously, such a dependence was constructed by Vigano and Mereghetti (2009), but for a more limited (by the number of bursts) and less homogeneous (including both short and long bursts) sample.

The vertical red dashed line indicates the possible position of GRB 190425 corresponding to the event S190425z on this dependence, according to the integrated number of counts measured by the SPI-ACS detector. The intersection of this line with the two dotted lines bounding the uncertainty band of the model dependence \(F_{\text{in}}(C)\) specifies the limiting values (at \(2\sigma\) significance) of the fluence from this burst in the energy range 10–1000 keV: \(F_{\text{min}} \approx 8.0 \times 10^{-8}\) erg cm\(^{-2}\) and \(F_{\text{max}} \approx 2.4 \times 10^{-6}\) erg cm\(^{-2}\) (see Table 1).

The red cross in this figure indicates the position of GRB 170817A corresponding to the event GW 170817 and the measurement errors of its fluences by the two instruments. The strong shift of the burst position leftward (and upward) relative to the best fit of the dependence \(F_{\text{in}}(C)\) probably reflects the fact of incomplete detection of photons from the burst by the SPI-ACS detector due to the already noted softness of its radiation (Pozanenko et al. 2018; recall that SPI-ACS is sensitive above 80 keV),

\(^5\)The interval used in constructing the spectrum and calculating the fluence in a given burst in the GBM catalog.

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