INTEGRAL detection of a long powerful burst from SLX 1735-269

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Abstract. We present results of analysis of a bursting behavior of a low mass X-ray binary system SLX 1735-269 during INTEGRAL observations of the Galactic Center region in 2003. There were detected 6 type I X-ray bursts in total, with one being much longer and more powerful then others. A strong dependence of the bursts recurrence time on the mass accretion rate is observed, that is likely caused by the change in the burning regime. The long burst demonstrated a photospheric radius expansion. We discuss possible scenarios of this long burst and show that it is unlikely a carbon burning flash and rather a burst of large pile of hydrogen and helium accelerated by electron capture processes in a dense accumulated layer.

Key words. X-rays: binaries – X-rays: individual: SLX 1735-269

1. Introduction

SLX 1735-269 was discovered as a persistent X-ray source in the energy range 3-30 keV in 1985 with the Spacelab 2 mission (Skinner et al. 1987). Since then the source was seen by different instruments with the flux level of \((2-5) \times 10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1}\) (Skinner et al. 1987, Pavlinsky et al. 1992, 1994, in ’t Zand 1992, Grebenev et al. 1996). SLX 1735-269 was detected in hard X-rays (35–75 keV) by the SIGMA telescope on board the GRANAT observatory in 1992 (Goldwurm et al. 1996). A broadband spectral analysis of the system showed that it is likely a low mass X-ray binary (David et al. 1997). But only in 1997 its nature was finally established after a detection of a type I X-ray burst with a Wide Field Camera on the BeppoSAX observatory (Bazzano et al. 1997, Cocchi et al. 1998). The detection of this type I burst (unstable nuclear burning on the neutron star surface, see e.g. Hansen & van Horn 1975) demonstrated that SLX 1735-269 is a neutron star binary system.

The burst detected with BeppoSAX/WFC remained the only one known burst from this system until the launch of the INTEGRAL satellite. A large exposure time spent by INTEGRAL on observations of the Galactic Center region allowed us to detect more bursts from SLX 1735-269. One of 6 detected bursts had a duration more than 1000 sec, that is not typical for standard hydrogen/helium type I bursts but rather similar to so-called superbursts – unstable burning of carbon (see e.g. Cumming & Bildsten 2001, in ’t Zand et al. 2003). In this paper we present the analysis of the bursting behavior of SLX 1735-269 concentrating on the properties of the unusual long burst.

2. Instruments and Observations

In this work we present results from the JEM-X monitor, module 2 (see Lund et al. 2003) and the upper layer of the IBIS telescope (ISGRI/IBIS; Ubertini et al. 2003) of the INTEGRAL observatory (Winkler et al. 2003a). These instruments together cover a broad energy range 3–400 keV with typical sensitivities \(\sim 4 \text{ and } 1.5 \text{ mCrab}\) for one orbit (\(\sim 3 \text{ days}\)) of observations for JEM-X (one unit) and IBIS/ISGRI, respectively.

In 2003 the Galactic Center region was observed many times with INTEGRAL during both Open and Core Programs of the observatory (Winkler et al. 2003b). In our analysis we used Galactic Center region observations of the Open Program performed in Aug. 23 - Sep. 24, 2003 (proposal ID 0120213) and publicly available data of Galactic Center observations performed as a part of the Core Program in Mar. 2 - Apr. 30, 2003. A total effective exposure of SLX 1735-269 for the JEM-X telescope was \(\sim 1.8 \text{ Msec}\), for the IBIS telescope \(\sim 3.4 \text{ Msec}\). The smaller effective exposure for JEM-X is caused mainly by its smaller field of view (all observational set consists of large number of pointings, and the optical axis of the observatory moves significantly from pointing to pointing).

Type I bursts have a very soft X-ray spectrum and a main part of its luminosity emitted in the energy range 3-10 keV, therefore for the search of X-ray bursts we used...
the data of the JEM-X telescope, collected from the whole detector.

JEM-X has five different telemetry formats: Full Imaging, Restricted Imaging, Spectral/Timing, Spectral and Timing. Usually it operates in a “full imaging mode”, when the data are recorded as an events list with the time resolution of 122 µsec and 256 energy channels information. This mode is preferable, but JEM-X has a very limited telemetry rate and sometimes it is forced to switch in to other modes. The count rate of its detector mainly dominated by a cosmic sources, therefore the telemetry rate of JEM-X strongly depends on a brightness of sources within its field of view (FOV). If the count rate of the detector exceeds some limiting value then on-board memory buffer reserved for JEM-X is overloaded and the information about all registered events can not be transmitted to the Earth. So, in this cases, in order to avoid gaps in the data transmission, a grey filtering algorithm is applied. Depending on the detector count rate this algorithm rejects “n” from “32” events. Thus, the real count rate equals to the transmitted count rate multiplied by 32/(1 + G), where G is a grey filter value, which can varies from “0” to “31”. If this algorithm can not keep count rate below the threshold, the restricted imaging mode is used. It has the time resolution 0.125 sec and 8 broad energy channels covering a whole JEM-X energy band. The grey filtering algorithm can be applied to this mode also, that leads to the significant worsening of the time resolution.

During our observations JEM-X was mainly in a “full imaging mode” but a few times it switched into a “restricted imaging mode”

3. Data reduction

The analysis of the JEM-X telescope data was done using a standard INTEGRAL Off-line Science Analysis software version 4.0 (OSA-4.0) distributed by the INTEGRAL Science Data Center.

The JEM-X analysis package from OSA-4.0 has twelve steps of the data treatment (see Chernyakova & Kretschmar, 2004, Part II). Below we discuss only three main levels: COR, IMA and SPE. COR is the first level of a scientific analysis where events after a primary telemetry pre-processing are corrected for instrumental effects, such as an energy gain correction and positional gain correction. An analysis up to IMA and SPE levels is based on the output data of the COR level. After the steps IMA and SPE we have reconstructed images of the sky and spectra of detected sources. For the following study we combined outputs of all three levels listed above.

It is important to note that at this moment the OSA software is still under the development and our investigations showed that a quantitative study of sources is not possible from the imaging. The measured absolute values of sources fluxes are not fully reliable while their detection and localization can be done with a high quality. Therefore we used the JEM-X imaging analysis only for the bursts localization.

For the timing analysis we used the data corrected for the instrumental effects (COR level, see above). Lightcurves were constructed from a total count rate of the JEM-X detector in required energy bands after the correction for the grey filter factor. As the detectors background only slightly variates with the time we used calibration observations of “empty fields” in order to determine the background level. To avoid problems with a vignetting correction in the following analysis we used only data when the source was in the JEM-X fully coded field of view (FCFOV). Applying this simplest procedure to the Crab observations we found that the background subtracted count rate of Crab is stable within ~ 20%. So using values of count rates of the Crab nebula in different energy bands and the background count rates in the same
energy bands we can get the absolute flux of a source in the FCOV of JEM-X with a rather good accuracy.

For the spectral analysis we used an outcome of OSA-4.0 (level SPE). The extensive study of Crab nebula observations showed that the software allows to reconstruct the shape of the source spectrum rather well while absolute fluxes are not reliable. Thus in the subsequent spectral analysis we used spectra produced by OSA-4.0, but renormalize them to the fluxes obtained from lightcurves (see above). The spectral analysis of the data obtained in the "restricted imaging mode" is not possible with OSA-4.0, therefore in this case we constructed source spectra from lightcurves in several broad energy bands.

The IBIS/ISGRI data analysis was done with the software developed by Eugene Churazov in Space Research Institute, Moscow [Revnivtsev et al. 2004]. This software provides the absolute values of source fluxes in a wide energy band with 10% systematic uncertainty and allows to reconstruct the spectrum shape with the accuracy of 3-5%.

Data of Rossi X-ray Timing Explorer (RXTE, Bradt, Rothschild & Swank 1993) observations that we used for the construction of SLX 1735-269 broadband spectra were reduced with the help of standard tasks of LHEASOFT 5.3 package.

4. Results

During all used observations 6 type I X-ray bursts were detected from SLX 1735-269 (see Table 1 and Fig.1). All of them with one exception have properties similar to that observed by BeppoSAX/WFC [Bazzano et al. 1997, Cocchi et al. 1998]. A typical profile of one of them (burst number #4 from the Table 1) is presented in Fig.2. All bursts demonstrated an exponential decay with e-folding time of \( \tau = 8 \pm 1 \text{ sec} \). Typical energies released in these bursts were approximately \( E_{\text{burst}} \sim \text{few} \times 10^{39} \text{ ergs s}^{-1} \) (here and later we will assume the source distance 8.5 kpc). Unfortunately a detailed spectral analysis is not possible for these bursts due to limited statistics.

An unusually long burst was observed on Sept. 15, 2003 at 17:35:14 UT during ultra deep Galactic Center observations (pointing number 011200540010). The count rate measured from the whole JEM-X detector and the grey filter factor during this observation are presented in Fig.3.

4.1. Profile of the long burst

In Fig.4 we present the profile of the long burst in different energy bands obtained from JEM-X data after the correction for the grey filter. Light curves in the subbands are background subtracted. The moment “0” corresponds to Sept. 15, 2003 17:35:14 (UT). The burst has a total duration more than 2 ksec and its profile demonstrates several notable features. To emphasize their we split the burst into four time intervals and plot each interval with its own time scale. The figure shows that the burst was started with a short burst-like event (“precursor”) that has a duration about ~ 2 sec and which was more powerful in soft energy bands. During ~ 8 sec after the precursor the source flux was below the detectable level. Such “gaps” are typical for bursts with the photospheric radius expan-

| #    | Start time, UT           | Burst type    |
|------|--------------------------|---------------|
| 1    | Apr. 15, 2003 09:48:35   | ordinary      |
| 2    | Sept. 15, 2003 17:35:14  | long          |
| 3    | Sept. 18, 2003 21:50:53   | ordinary      |
| 4    | Sept. 20, 2003 22:01:37   | ordinary      |
| 5    | Sept. 21, 2003 10:37:15   | ordinary      |
| 6    | Sept. 23, 2003 23:13:05   | ordinary      |
Fig. 4. Temporal profiles of the long burst measured by JEM-X in different energy bands. All light curves are corrected on the grey filter factor. Time binning for the light curve in the broad energy band (upper panel) is 5 sec for the “full imaging mode” and 8 sec for the “restricted mode”. Time binning for other curves is pointed in the figure.

... and can be interpreted in terms of the cooling of the neutron star photosphere during its expanding. After this “gap” the flux of the source rise again to the maximum during $\sim 100$-$450$ sec depending on the energy band. Such behavior reflects a strong change of the source hardness and is also typical for bursts with the photospheric radius expansion (a contraction phase). The source intensity decay after $\sim 450$ sec can be characterized by e-folding time $\tau \sim 250$ sec in the energy band 2-7 keV and $\tau \sim 150$ sec in the 15-23 keV energy band.

In the tail of the burst can be seen quasiperiodic oscillations of the source flux at the time scale of $\sim 100$ sec. Such oscillations are practically not visible in the harder energy band (10-23 keV) that indicates that the amplitude of these variations decreases with the energy. Interesting to note that the time scale and energy dependence of these oscillation are very similar to those of mHz QPOs, seen in some other X-ray bursters (Revnivtsev et al. 2001). In this paper authors proposed...
that such oscillations can be caused by some special regime of the nuclear burning on the neutron star surface.

4.2. Spectral evolution during the burst

For the spectral analysis we extracted a source spectrum during a 2 sec time interval covering the precursor, 17 consecutive spectra started from ~ 20th sec with an integration time of 20 sec, and 6 spectra in the restricted imaging mode. All obtained spectra were fitted by a blackbody model in the 3-20 keV energy band.

In the two upper panels of Fig. 5 evolutions of burst fluxes in the JEM-X 7-10 keV and ISGRI/IBIS 18-22 keV energy bands are shown in mCrab units. In the middle panel we present the bolometric luminosity of the source (in units of $10^{38}$ ergs s$^{-1}$) calculated from the blackbody spectral model as a function of time.

The fit of the spectrum obtained during the precursor by this model gives following parameters: $T_{bb} = 1.1 \pm 0.2$
keV and $R_{dd} = 26 \pm 7$ km. Such large uncertainties are caused by a limited sensitivity of JEM-X for such weak and soft events. During the next $\sim 8$ sec after the precursor the flux from the source was not detected. The evolution of the model parameters during the following $\sim 1000$ sec is presented in two lower panels of Fig.6.

5. Discussion

5.1. Bursts and persistent flux

Before INTEGRAL only one type I X-ray burst was detected from SLX 1735-269. This burst had a duration of $\sim 30$ sec (e-fold decay time $\sim 10$ sec) and a peak flux approximately 900 mCrab [Bazzano et al. 1997]. Cocchi et al. 1998] which translates into the energy emitted in the burst few $\times 10^{39}$ ergs (assuming a source distance of 8.5 kpc). Such energy release and decay time are typical for the helium burning regime (see e.g. Fujimoto, Hanawa & Miyaji 1981, Bildsten 1998).

INTEGRAL observations of the source in 2003 contain approximately 1.8 million seconds of exposure time for the JEM-X monitor. During this exposure we have detected in total 6 X-ray bursts. One of them was extremely powerful and long, while others were similar to that one observed by BeppoSAX. This long burst obviously had much longer recurrence time. No any bursting activity was detected during $\sim 11$ days (an effective exposure) before this burst. It is important to note that there were small gaps in our observations, but their total duration was not significant (Fig.1).

Several short consequent bursts allow us to estimate the burning regime parameter $\alpha$, the ratio between an accretion energy released between bursts to a nuclear energy released in the burst. This parameter in some way reflects the composition of the burning fuel. Using the set of almost consequent bursts detected from day 25 till day 33 (in the units of Fig.1) we estimated $\alpha \sim 100 - 200$ (different estimations of $\alpha$ appear because of not clock-like bursting behavior of SLX 1735-269). Such values of $\alpha$ are typical for almost pure helium burning [Fujimoto, Hanawa & Miyaji 1981, Bildsten 1998, Woosley et al. 2004].

In order to obtain the best estimation of the source luminosity and accretion rate we should to construct the source broadband spectrum because the hard X-ray information alone is not a good estimator of the total broadband or bolometric luminosity of neutron stars (e.g. Barret 2001). In order to reconstruct the source broadband spectrum we included data of the RXTE observatory in our analysis.

One observation of SLX 1735-269 was performed as a part of a coordinated INTEGRAL+RXTE observational campaign of the system. At that time the source spectrum was hard, with a photon index $\Gamma = 2.0 \pm 0.1$ and an exponential cutoff at energies $E_{\text{cut}} = 150^{+50}_{-10}$ keV (see Fig.4). The model broadband (0.5-100 keV) flux of the source was $\sim 5.4 \times 10^{-10}$ erg s$^{-1}$ cm$^{-2}$ that corresponds to the source luminosity $L_x \sim 4 \times 10^{36}$ ergs s$^{-1}$. During the period of a low hard X-ray flux the source has a completely different spectrum. INTEGRAL observations show that the spectrum became much softer than it was during the period of high hard X-ray flux. We searched the public RXTE data archive in order to find the source spectrum similar to that observed by INTEGRAL during the period of low hard X-ray (18-60 keV) flux. RXTE observations of SLX 1735-269 performed on Feb. 14, 2003 perfectly match this criterion. The total broadband (0.5-100 keV) flux of the source in this state increased and the cutoff energy strongly diminished ($E_{\text{cut}} = 11 \pm 1$ keV) in the comparison with the period of a large hard X-ray flux (Fig.4). The broadband (0.5-100 keV) flux at this state was $\sim 6.2 \times 10^{-10}$ erg s$^{-1}$ cm$^{-2}$ that corresponds to the source luminosity $L_x \sim 5 \times 10^{36}$ ergs s$^{-1}$.

Note that the observed source luminosities differ only slightly while its spectrum shape and burst properties differ dramatically. During the soft state type I bursts go quite often – the recurrence time between the bursts is approximately 0.5-2 days. In contrast to this then the source spectrum was very hard the recurrence time strongly increases – $\Delta t_h > 11$ days. This can indicate that the source persistent accretion rate is on the border between two

\[ E_{\text{cut}} = 11 \pm 1 \text{ keV} \]

\[ L_x \sim 5 \times 10^{36} \text{ ergs s}^{-1} \]
distinct modes of a nuclear burning. A theory says that such transition should occur approximately at the value of $\sim 10^3$ g s$^{-1}$ cm$^{-2}$ mass accretion rate per units area (e.g. Bildsten 1998). The persistent mass accretion rate on the neutron star in SLX 1735-269 (assuming $\eta \sim 20$% mass to energy conversion coefficient and $L = \eta M c^2$) is $\dot{M} \sim 2 \times 10^{16}$ g s$^{-1}$. The corresponding accretion rate per unit area is $\dot{M} \sim 1.5 \times 10^3$ g s$^{-1}$ cm$^{-2}$ (assuming 10 km radius of the neutron star). Therefore indeed we have the system in which the accretion rate is on the border of two regimes of the nuclear burning. Note that this supports the assumption of the source distance 8.5 kpc.

Short bursts with e-folding time $\tau \sim 10$ sec are rather typical among type I bursters. Very long bursts, with a duration more than 1000 sec are rare and a present theory provides two possible scenarios for such bursts – the burning of a large pile of hydrogen and helium fuel, or the carbon flash (see e.g. Kuulkers et al. 2002).

5.2. Carbon flash scenario

The source accretion rate per unit area $\dot{M} \sim 1.5 \times 10^3$ g s$^{-1}$ cm$^{-2}$ does not allow to burn of He in a stable manner (Bildsten 1998). Therefore the accumulation of a large amount of carbon can not be done via this process and the most of the carbon fuel needed to produce the burst should be accreted from a companion star. An estimation of the energy released in the burst gives $E_{\text{burst}} \sim 2 \times 10^{41}$ ergs. To provide such energy with the carbon fuel (a nuclear energy release $\sim 5.6 \times 10^{17}$ ergs g$^{-1}$, Cumming & Bildsten 2001) we should burn $\dot{M} \sim 5 \times 10^{23}$ g of carbon. To accumulate such amount of carbon via accretion from the main sequence secondary star we need more than $10^9$ sec (assuming a solar abundance of $^{12}$C in the accreted matter). Therefore the probability to detect one burst in our set of observations (an effective exposure time $\sim 2 \times 10^6$ sec) is less than one tenth of percent. Thus we conclude that the long burst from SLX 1735-269 is very unlikely a carbon one.

5.3. He/H flash scenario

The theory says that for such low accretion rate an X-ray burst can be caused by a mixed hydrogen and helium burning triggered by a hydrogen ignition accelerated by electron capture processes (see e.g. Fushiki et al. 1992, Bildsten 1998, Bildsten & Cumming 1998, Kuulkers et al. 2002). The nuclear energy release per gram of such fuel is $\sim$ few $\times 10^{18}$ ergs g$^{-1}$ (depending on the fuel composition). We should to burn $\sim 10^{23}$ g, which will be accumulated after $\sim 3 \times 10^6$ sec of the accretion with the above mentioned rate. This recurrence time is comparable with the exposure of our observations. The critical surface density necessary to make electron capture processes very effective is or the order of $y \sim 10^{10}$ g cm$^{-2}$, that means that the accreted mass $M \sim 10^{23}$ g of the matter should be involved. This value again is compatible with the observed value of the mass burned in the long burst.

The length of the burst in this scenario mainly depends on the limiting (Eddington) luminosity. It is governed by the energy budget of the burst divided by the Eddington luminosity on the neutron star. A stability of the source luminosity during a few hundreds of seconds at the peak of the burst (Fig.4) supports this assumption.

Summarizing all of the above we can conclude that the long burst detected from SLX 1735-269 most likely is a result of the unstable burning of a large pile of mixed hydrogen and helium accelerated by electron capture processes. It is interesting to note that the similar long burst was observed by BeppoSAX from another faint neutron star binary SLX 1737-282 (In ‘t Zand et al. 2002).

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