REGISTRATION OF THE FIRST THERMIONUCLEAR X-RAY BURST FROM AX J1754.2-2754

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During the analysis of the INTEGRAL observatory archival data we found a powerful X-ray burst, registered by JEM-X and IBIS/ISGRI telescopes on April 16, 2005 from a weak and poorly known source AX J1754.2-2754. Analysis of the burst profiles and spectrum shows, that it was a type I burst, which result from thermonuclear explosion on the surface of neutron star. It means that we can consider AX J1754.2-2754 as an X-ray burster. Certain features of burst profile at its initial stage witness of a radiation presure driven strong expansion and a corresponding cooling of the neutron star photosphere. Assuming, that the luminosity of the source at this phase was close to the Eddington limit, we estimated the distance to the burst source $d = 6.6 \pm 0.3$ kpc (for hidrogen atmosphere of the neutron star) and $d = 9.2 \pm 0.4$ kpc (for helium atmosphere).

Key words: X-ray sources, transients, accretion

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INTRODUCTION

X-ray burster AX J1754.2-2754 was first observed on October 2–3, 1999 by ASCA (Sakano et al., 2002) orbital observatory. Its 0.7–10 keV flux reached \( \sim 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \) (\( \sim 0.3 \text{ mCrab} \)). The source had a power law spectrum with an index \( \alpha \sim 2.5 \), modified at low energies by interstellar absorption corresponding to \( N_{\text{H}} \sim 2 \times 10^{22} \text{ cm}^{-2} \). Types of the source and its compact object were not determined at that time. AX J1754.2-2754 was registered (at the IBIS/ISGRI sensitivity limit — with \( 2.05 \pm 0.53 \text{ mCrab} \) in 17-60 keV energy band) later during a hard X-ray INTEGRAL observatory 2003-2006 all-sky survey (Krivonos et al., 2007). These observations as well failed to discover its true nature.

In this paper we report the discovery of type I X-ray burst from this source with INTEGRAL observatory telescopes (see also Chelovekov, Grebenev, 2007) and present the results of its detailed analysis. Registration of this burst puts AX J1754.2-2754 in a group of X-ray bursters, so the compact object in this source is a neutron star.

INSTRUMENTS AND OBSERVATIONS

INTEGRAL (Winkler et al., 2003) is an international orbital \( \gamma \)-observatory, that was put to its high apogee orbit by the PROTON launcher on October 17, 2002 (Eismont et al, 2003). The observatory consists of four telescopes, meant to perform simultaneous observations in \( \gamma \)-ray, X-ray and optical energy bands. In this paper we use data from JEM-X X-ray monitor (Lund et al., 2003) and ISGRI (Lebrun et al., 2003) — one of two detectors of the IBIS (Ubertini et al., 2003) \( \gamma \)-ray telescope. Both of these instruments use a principle of coding aperture to construct images of the sky in the field of view and study individual sources.

JEM-X monitor is sensitive to photons in 3–35 keV energy band and has a field of view of 13\(^\circ\)2 in a diamiter (with only 4\(^{\circ}\)8 of it fully coded) and an angular resolution of 3\(^{\prime}\)35 (FWHM). A gas chamber with entrance window area of 490 cm\(^2\) and an energy resolution \( \Delta E/E \sim 16@6\text{keV}\% \) (FWHM) is used as a position-sensitive detector. The effective detector area for sources in the center of the field of view is just \( \sim 75 \text{ cm}^2 \), for more then 80% of the detector is shaded by opaque mask elements and collimator.

The ISGRI detector consists of 128\(\times\)128 CdTe semiconductor elements, with maximum sensitivity in a 18–200 keV energy band. Its energy resolution is \( \Delta E/E \sim 7\% \) (FWHM). The total area of the detector is 2620 cm\(^2\) and the effective area for sources in the center of the field of view is \( \sim 1100 \text{ cm}^2 \) (half of the detector is attenuated by opaque mask elements). The IBIS telescope has a field of view of 30\(^\circ\) × 30\(^\circ\) (9\(^\circ\) × 9\(^\circ\) of it is fully coded) and an angular resolution of 12\(^{\prime}\) (FWHM). Such a resolution allows one to determine the position of bright sources with up to 2\(^{\prime}\) accuracy.

An X-ray burst from AX J1754.2-2754 was registered on April 16, 2005 — during the deep (very large exposure) observation of the Galactic Center region by INTEGRAL observatory. But it was discovered much later (see Chelovekov, Grebenev, 2007) — as one of the results of the project, dedicated to X-ray bursts search in open (for public access) archival
IBIS/ISGRI telescope data of the INTEGRAL\(^1\) observatory. Data analysis methods, used in this research are described in detail in paper by Chelovekov et al. (2006). A later check revealed the burst under discussion in JEM-X telescope data as well.

**BURST PROFILE**

Fig. 1 shows JEM-X telescope lightcurve in 3–20 keV energy band during \(\sim 400\) s interval including the burst. A dashed line shows the preburst countrate level due to persistent emission of the sources in the field of view of the telescope as well as cosmic and instrumental backgrounds. Burst profile had a sharp (rise time \(\sim 10\) s) raise and a long exponential decay (exponential decay time \(t_e = 67 \pm 3\) s in the mentioned energy band). Such a profile is typical of type I X-ray bursts (it is often referred to as FRED — Fast Rise Exponential Decay). Maximum countrate (corresponding to \(\sim 2\) Crab) was reached at UT 22\(^{h}\)10\(^{m}\)25\(^{s}\).

An initial phase of the burst profile with a better time resolution is shown in the inset. One can see a fairly complex structure of the profile — it is even possible to assume the presence of a separate narrow (of \(\lesssim 2\) s duration) peak (precursor) \(\sim 5 – 6\) s before the burst maximum.

It is of no lesser interest to study the burst profile with a better energy resolution and trace how its shape changes with energy. Fig. 2 (panels from top to bottom) shows JEM-X burst profiles in 3–6, 6–12, 12–20 keV energy bands and IBIS/ISGRI burst profiles in 15–20 and 20–40 keV energy bands. While constructing all of these profiles as well as the profile on fig. 1, we used all the detector events with no regard to the arrival direction of the origin photons. All of these profiles are corrected for detector deadtime. All JEM-X profiles are also corrected for “grey” filter, used in case of large countrates (Lund et al., 2003).

Fig. 2 shows, that during initial (\(\lesssim 20\) s) and final (\(\gtrsim 80\) s) burst phases very soft radiation (3–6 keV) is dominant in its profile. After reaching maximum in \(\sim 10\) s after the beginning of the burst it started to decay rapidly with a characteristic time \(t_e = 31 \pm 6\) s, but then, after \(\sim 30\) s, the decay flattened. The 6–12 keV emission reached its maximum in \(\sim 20\) s after the beginning of the burst and later decayed with an exponential decay time \(t_e = 115 \pm 6\) s. Hard (12–40 keV) emission appeared only for comparatively short time interval (20–80 s) and reached its maximum around UT 22\(^{h}\)11\(^{m}\)04\(^{s}\) (\(\sim 50\) s after the beginning of the burst). Burst profile in this energy band had almost triangular shape. All these features are typical of type I X-ray bursts, which are associated with thermonuclear explosions of the matter, stored on the surface of the neutron star during the accretion in a binary system. The possible presence of the burst precursor and the registration of very soft radiation during the initial phase of the burst suggest that the neutron star atmosphere expansion due to Eddington critical luminosity of the source could take place at this phase.

\(^1\)While preparing the paper we found out, that this burst caused an Integral Burst Announcement System alert (event #2463). IBAS scientists spread the message (Merghetti et al., 2005) over GCN, reporting the event as most likely not the actual GRB and pointing to a possible source of the observed activity — AX J1754.2-2754. However, the properties and type of the burst as well as the nature of the source were not discussed in the report.
LOCALIZATION

Fig. 3a shows an image (map of the signal to noise ratio $S/N$), built based on IBIS/ISGRI data in 15–25 keV energy band accumulated during first 70 s of the burst. Many sources including well known X-ray bursters such as GX3+1, A1742-294, SLX 1744-299/300, GRS 1741.9-2853 (see fig. 3b) are situated within the field under consideration, but the image makes it clear, that none of them but AX J1754.2-2754 was the source of the burst. It was the only significant ($S/N \simeq 16$, mean flux was $660 \pm 40$ mCrab) source detected during these 70 s in the field of view of the telescope.

Fig. 4a and b show similar, but smaller 3–20 keV JEM-X images. For this figure we specially used a field of the sky, including an X-ray burster GX 3+1. Despite its brightness (see fig. 4b), this source was not detected during 70 s of the burst by JEM-X telescope at significant level, unlike AX J1754.2-2754 ($S/N \simeq 32$). At the same time, another very bright source GX 5-1 ($S/N \simeq 22$) was registered in the field of view of the telescope, but it is not a burster. Besides, IBIS/ISGRI data leaves no doubts that the burst came from the immediate neighborhood of AX J1754.2-2754.

A more accurately determined position of the burst source according to JEM-X data $R.A. = 17^{h}54^{m}12^{s}$, $Decl. = -27^{\circ}54'58''$ (epoch 2000.0, uncertainty 1'), shows that it is $33''$ away from the position of AX J1754.2-2754, determined by the ASCA satellite. Burst source position derived from IBIS/ISGRI data, $R.A. = 17^{h}54^{m}13^{s}$, $Decl. = -27^{\circ}54'11''$ (uncertainty 2'), is $41''$ away from this AX J1754.2-2754 position. So it is obvious, that precisely AX J1754.2-2754 was the source of the burst.

BURST SPECTRUM

Fig. 5 shows the average spectrum of the burst in $\nu F_\nu$ units, obtained by JEM-X (filled circles) and IBIS/ISGRI (empty circles) telescopes during its first 70 s. A best spectrum approximation with black body model is shown by solid line. We assumed that the interstellar absorption for this source corresponds to the hydrogen column density $N_H = 2 \times 10^{22}$ cm$^{-2}$ for solar elemental abundance. Parameters of the approximation — black body temperature $kT_{bb} = 2.10 \pm 0.04$ keV and neutron star photosphere radius $R_{bb} = 10.3 \pm 2.9$ km — are in a good agreement with those measured for other bursters. At the same time fig. 5 and the high value of $\chi^2 = 2.1$ normalized for number of degrees of freedom for this approximation show, that the fit is far from the ideal and this discrepancy may well be expected. The burst spectrum may be strongly modified by comptonization in the neutron star atmosphere, and even more than that: the average spectrum under discussion is a complicated combination of black body spectra with different values of temperature, emitted at different stages of the burst.

To trace the evolution of the X-ray burst spectrum we constructed and studied “prompt” spectra for eight successive time intervals of 10 s duration each. Fig. 6 presents the results of this analysis. The spectrum for the interval, separated by $\sim 50$ s from the beginning of the burst was the hardest as it was clear even from the comparison of burst profiles (fig. 2). It is important to mention, that estimated value of neutron star photosphere black body radius for the first 10 s interval was more then five times higher, then the ones for other
time intervals, while the black body temperature of the photosphere was lowest (∼ 1 keV) during this interval. It is obvious than, that a photospheric expansion took place during this interval due to luminosity reaching the Eddington limit value.

Fig. 3 and 4 show, that the average AX J1754.2-2754 persistent X-ray flux over the entire observing session, including the burst (∼ 3 days), is below the level of significant detection by JEM-X and IBIS/ISGRI telescopes. A 3σ upper limit for the 18-45 keV flux from the source in case of IBIS/ISGRI was 1.7 mCrab.

DISCUSSION

Our analysis shows, that X-ray burst, registered by INTEGRAL observatory telescopes on April 16, 2005 from AX J1754.2-2754 was of type I - a burst resulting from thermonuclear explosion on the surface of the neutron star. Registration of this burst determines a nature of a compact object in this source — it is a neutron star. Certain features of the initial phase of the burst profile are typical of neutron star photosphere expansion and cooling, which suggests, that luminosity of the source reached a critical Eddington limit $L_{ed} \simeq 2.8 \times 10^{38}\left(M/M_\odot\right)\left(1 + X\right)$ erg s$^{-1}$, where $M$ is a mass of neutron star and $X$ is a hydrogen abundance in its atmosphere. Assuming the neutron star mass to be $1.4 M_\odot$, we estimated the distance to AX J1754.2-2754

$$d = \left(\frac{L_{ed}}{4\pi F_{max}}\right)^{1/2} \simeq 6.6 \pm 0.3 \text{ kpc},$$

for a hydrogen atmosphere ($X = 1$) and $d \simeq 9.2 \pm 0.4 \text{ kpc}$ for a helium atmosphere ($X = 0$). Here $F_{max} = (3.84 \pm 0.15) \times 10^{-8} \text{ srg cm}^{-2} \text{ s}^{-1}$ is a maximum flux, registered during the burst. It is important to mention, that the vast bulk of burst energy is emitted in 3–20 keV energy band (see fig. 5).

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Fig. 1: A profile of an X-ray burst from AX J1754.2-2754, registered on April 16, 2005 by JEM-X telescope (3–20 keV energy band, axis gives time in seconds from the beginning of pointing UT 21$^{h}$58$^{m}$35$^{s}$, time resolution is 5 s). The curve is corrected for a detector deadtime and a “grey” filter coefficient. The initial phase of the burst with a smaller time resolution (1 s), to show its complex structure with a possible precursor, is presented in the inset.
Fig. 2: A profile of an X-ray burst from AX J1754.2-2754, in various energy bands registered on April 16, 2005 by JEM-X and IBIS/ISGRI telescopes (axis gives time in seconds from the beginning of the observation UT 21\textsuperscript{h}58\textsuperscript{m}35\textsuperscript{s}, time resolution is 5 s). All the curves are corrected for detector deadtime, all JEM-X curves are also corrected for “grey” filter coefficient.
Fig. 3: Images of a $2'6 \times 2'3$ sky region in the IBIS/ISGRI field of view: (a) during the X-ray burst, registered from AXJ1754.2-2754 (70 s exposure, 15–25 keV energy band), and (b) over the entire observing session (the entire orbit), except the pointing, including the burst itself (201600 s exposure, 18–45 keV energy band). The contours show areas of sources registration at signal-to-noise ratios $S/N = 4.5, 5.4, 6.4, 7.7, 9.1, 11, 13, 16, ..., 45$. 
Fig. 4: Images of a $1.9 \times 1.9$ sky region in the JEM-X field of view obtained in the 3-20 keV energy band: (a) during the X-ray burst, registered from AX J1754.2-2754 (exposure 70 a), and (b) over the entire observation session, except for the observation, including the burst itself, and some observations, during which the observatory was pointed more than 5$^\circ$ away from the source under consideration (exposure 97400 s). The contours show areas of sources registration at signal-to-noise ratios $S/N = 4.5, 5.4, 6.4, 7.7, 9.1, 11, 13, 16, 19$. 
Fig. 5: Average spectrum of the X-ray burst from AX J1754.2-2754, obtained by JEM-X telescope (filled circles) and IBIS/ISGRI telescopes (empty circles) during first 70 s of the burst. The solid line shows a black body model approximation of the spectrum.
Fig. 6: Evolution of AX J1754.2-2754 spectrum parameters during the X-ray burst in a black-body radiation model (from top to bottom: evolution of temperature, radius of the emitting body, bolometric luminosity, observed 3–20 keV luminosity.)