Broadband X-ray spectrum of XTE J1550-564 during 2003 outburst

©2004 V.A.Arefiev, M.G.Revnivtsev, A.A.Lutovinov, R.A. Sunyaev

1 Space Research Institute, Moscow, Russia
2 Max-Planck-Institut fuer Astrophysik, Garching, Germany

Results of broadband INTEGRAL and RXTE observations of the Galactic microquasar XTE J1550-564 during outburst in spring 2003 are presented. During the outburst the source was found in a canonical low/hard spectral state.

1. Introduction

X-ray transient source XTE J1550-564 was discovered with all sky monitor ASM onboard the RXTE observatory on September 7 1998 (Smith, 1998). Soon its optical and radio counterparts were identified by Orosz 1998, Campbell-Wilson et al., 1998. During the outburst in 1998-1999 the source have demonstrated all canonical spectral states of black hole binaries – high/soft, low/hard and intermediate. Spectral and temporal variability of the source was very complicated (Homan et al., 2001). After two weeks of the source discovery a giant X-ray flare was observed, when the source flux reached the value of 6.8 Crab (Remillard et al., 1998). Luminosity, that corresponds to this flux was $9.4 \times 10^{38}$ erg/s in the energy band 2-100 keV (assuming the source distance 5.3 kpc, Orosz et al., 2002), that approximately equals to the Eddington luminosity for this source. Recently CHANDRA observations revealed weak X-ray emission of relativistic jets associated with the source, which, according to their velocity and distance from the source, can be launched during its near-Eddington flare (Tomsick et al., 2003). Relativistic jets of the system, that also were observed in the radio band (Hannikainen et al., 2001), allowed to classify XTE J1550-564 as a microquasar. Optical observations demonstrated that the binary system has orbital period 1.54 days and the mass of the compact object is $M \sim 10 M_\odot$ (Orosz et al., 2002), that is significantly higher than that it is supposed to be possible for a neutron star.

XTE J1550-564 demonstrated a set of strong outbursts: in 2000 (Tomsick et al., 2001a, Rodriguez et al., 2003), 2001 (Tomsick et al., 2001b), 2002 (Belloni et al., 2002) and 2003 (Dubath et al., 2003), however none of these outbursts were as complex and powerful as the first one (see Fig. 1). All subsequent outbursts had more or less standard shape of the lightcurve, with fast rise and slow decay, and practically had no spectral variability. It is very curious that the time difference between consequent outbursts is approximately 1 year and stays like that during last 6 years, while the source was never (at least 25 years) observed before 1998.

In this paper we present results of analysis of observations of XTE J1550-564 with INTEGRAL (Core program data) and RXTE observatories (publicly available slew data) during its 2003 outburst.

2. Data analysis and results

International gamma-ray observatory INTEGRAL (Winkler et al. 2003a) was launched by a Russian rocket-launcher PROTON on Oct.17 2002 (Eismont et al. 2003). The observatory have four instruments, that allow one to study cosmic X-ray sources in X-ray, gamma and optical bands. As a part of the Core program the INTEGRAL observatory performs systematic scans of the Galactic plane searching for the X-ray transients and studying the variability of detected sources (Winkler et al. 2003b). During one of such scans in spring of 2003 a beginning of a new outburst of XTE J1550-564 was detected (Dubath et al. 2003).

During INTEGRAL observations of the Galactic plane XTE J1550-564 was mainly out of the field of view of the JEM-X monitor (except for TOO INTEGRAL observations of this source, which we do not consider here), therefore we will use in this work the data of the IBIS telescope (detector ISGRI, Lebrun et al. 2003) and spectrometer SPI (Vedrenne et al. 2003), that have large fields of view ($29^\circ \times 29^\circ$, $35^\circ \times 35^\circ$, respectively).

Data of IBIS/ISGRI were reduced using the method described by Revnivtsev et al. (2004). Analysis of the SPI data was performed with the help of standard package OSA 3.0 1. For the reconstruction of the source spectrum

http://isdc.unige.ch/index.cgi?Soft+soft
from the data of IBIS/ISGRI we used the ratio of the source fluxes in different energy bands to those of the Crab nebula, assuming the spectrum of the Crab in the form \( dN(E) = 10E^{-2.1}dE \) ph cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\). In order to check the correctness of the applied algorithms and to estimate the amplitude of systematic uncertainties we studied a large set of Crab nebula observations. Results of this analysis show that with the used software we still have 2-5% systematic uncertainties in the spectral reconstruction and \( \sim 10\% \) in the absolute flux value estimation. Analysis of SPI data with the OSA 3.0 package systematically gives overestimated flux from the source, while provides a correct spectral shape reconstruction. Therefore in the subsequent analysis we will renorm the SPI flux values to those obtained with the help of IBIS/ISGRI.

As the source was out of the field of view of JEM-X monitor in order to complement the obtained hard X-rays information with the standard X-ray band we analyzed publicly available data of the RXTE observatory — data of the all sky monitor ASM and slew parts of observations of spectrometer PCA, performed in the period March 27 - April 21, 2003. Data of the RXTE/PCA were reduced with standard tasks of the LHEASOFT/FTOOLS 5.3 package. In order to reduce systematic uncertainties in the output spectra we limited ourselves with the data of only upper anode layers of the PCA detectors and excluded data of PCU0 detector from our analysis, because since 2000 it lacks propane veto layer.

**Lightcurve**

INTEGRAL observed XTE J1550-564 several times during the spring of 2003 performing the Galactic plane scans. From the beginning of March 2003 and to the first detection of XTE J1550-564 on March 24 the source position was observed by INTEGRAL/IBIS during \( \sim 300 \) ksec. An upper limit on the averaged source flux during this time is approximately 1-2 mCrab in the 18-60 keV energy band.

The outburst, first detected by the IBIS telescope, started on March 24.2, 2003 (Dubath et al., 2003). Then source several times was in the field of view of INTEGRAL during the rising phase of the outburst and at the peak of its lightcurve (March 24-25 and April 8,2003). The X-ray light curve obtained by INTEGRAL and RXTE is presented in Fig.2. It is seen that the overall length of the outburst in the standard X-ray energy band (RXTE data) equals approximately 50 days, the shape of the light curve is slightly asymmetric with the raise phase \( \sim 10 \) days, and more smooth decay on a time scale of \( \sim 35 - 40 \) days. Because of limited amount of available INTEGRAL data we can not determine the length of the outburst in the hard X-ray and gamma energy bands. However, we can note that the maximal flux of the source detected in the soft/standard X-ray band \( \sim 70 \) mCrab) is significantly lower than that seen in the hard X-ray band \( \sim 200 \) mCrab), that indicates that the source had a hard spectrum.

**Spectrum**

Preliminary analysis of spectra of XTE J1550-564 showed that during the outburst the source demonstrated only subtle spectral variability. Because of that in order to improve statistics we will use spectrum of the source averaged over all observations.

The Broadband averaged spectrum of XTE J1550-564, obtained by INTEGRAL and RXTE observatories during the source outburst in 2003 is presented in Fig.3. Also for comparison we present the spectra of the source averaged over hard state periods of its outbursts in 2000 (see e.g. Rodriguez et al., 2003) and 2001. It is seen that spectra of 2001 and 2003 are significantly harder that that of 2000.

Standard model of the accretion flow in the black hole binaries in their low/hard spectral states considers that the optically thick and geometrically thin accretion disk ends (Poutanen et al. 1997), for example evaporates (Meyer et al., 2000), at distances of the order of \( \sim 10 - 100R_g \) from the black hole and most of the energy release occurs in the optically thin hot plasma cloud at \( R < 10 - 100R_g \). X-ray spectrum originates as a result of the comptonization of photons in this hot region (see e.g. Sunyaev, Titarchuk, 1980). Part of this hard spectrum can be reflected from outer optically thick cold accretion disk (Basko et al., 1974; George, Fabian 1991). For the spectral approximation of obtained data we used the compontization model of Poutanen&Svensson (1996) (model *compps* in the spectral package XSPEC), which includes the reflection from the cold medium. This model describes the cutoff of the comptonized spectrum at high energies more correctly than simple analytic approximation in the form \( F \propto E^{-1,5} \exp(-E/kT) \). Temperature of the seed photons was fixed at the value of 0.1 keV. Best fit parameters of the applied model are presented in Table 1. Note that the obtained optical depth of the comptonizing cloud is rather high \( \tau \approx 4 - 5 \), that is not very typical for accreting black holes in the hard state. However, it can indicate that due to possibly high inclination of the system we are looking to the central source through whole depth of the hot cloud.

In the spectral approximation we assumed systematic uncertainties at the level of 1% and 5% at every energy channel for RXTE/PCA and INTEGRAL/IBIS respectively. An absorption column at the line of sight to the source was fixed at the value \( N_H = 10^{22} \) cm\(^{-2}\) determined by CHANDRA (Kaaret et al., 2003).

It is necessary to note that the present uncertainties in the crosscalibration of the RXTE/PCA and INTEGRAL/IBIS+SPI influence on the best fit parameter of the reflection \( R = \Omega/\pi \). Therefore, in spite of statistically significant detection of the reflected component in the spectrum of XTE J1550-564 this value should be treated with care.

An absolute width of the Fe fluorescent line at \( E \sim 6.4 \) keV was fixed at the value of \( \sigma = 0.1 \) keV (undetectable width for the RXTE/PCA) for all spectra, except for that
of 2000 outburst. In this spectrum the width was determined to be $\sigma \sim 0.6 - 0.7$ keV.

3. Discussion

The X-ray transient XTE J1550-564 is located in the Galactic plane approximately 4° away from well known bright X-ray source Cir X-1 in the region that was observed by different instruments/observatories. After at least 25 years of the off-state the source entered to the new phase, in which it generates outbursts approximately every year. Such a behavior is drastically differ from usual behavior of black hole X-ray transients

During two first outbursts (1998-1999 and 2000) the source demonstrated numerous and complicated spectral transitions (it is especially applicable to the first outburst). During the first outburst (Fig.1, MJD 51036-51299) the source was observed in the soft/high spectral state and demonstrated $M$-like light curve not only in the standard X-ray energy band but also in the broad (2-200 keV) band

Alexandrovaich, Areifev 2002. Sobczak et al. (2000) described the spectrum of the source in this state as a sum of two components – a multicolor optically thick accretion disk (Shakura&Sunyaev 1973) and a power law. In the first phase of the outburst (before ~ MJD 51150) the power law component dominated, while later the disk component contributed the most to the observed X-ray emission.

Second outburst (2000) was less violent, the source flux reached the value 1 Crab in the energy band of the RXTE/ASM, and the source behavior was much simpler: at the beginning and at the end of the outburst when the source X-ray flux was low it demonstrated the hard spectrum (Rodriguez et al. 2003). At the maximum of the outburst the source changed its state into the intermediate, when significant contribution from the accretion disk was visible.

Rodriguez et al. (2003) have found that during 2000 outburst the transitions between low and intermediate states have demonstrated hysteresis effect. First transition from low to intermediate state happened at the flux level $\sim 2.3 \times 10^{-8}$ ergs cm$^{-2}$ s$^{-1}$ in the energy band 2-200 keV, while the back transition from intermediate to low state happened at $\sim 1.1 \times 10^{-8}$ ergs cm$^{-2}$ s$^{-1}$. Indications on such hysteresis effect can be also found in the first outburst. As it was found in the work of Sobczak et al. (2000) during first two days of the outburst of 1998-1999 the photon index of the source spectrum was less than 2 while the source flux was lower than few $10^{-8}$ erg cm$^{-2}$ s$^{-1}$. Contribution of the soft disk component at that time was not very significant (around 5% of the total flux). A comparison of the data of RXTE/PCA and CGRO/BATSE (Alexandrovaich & Areifev 2002) support the assumption that the source during MJD 51063-51066 was in the low/hard state. After the transition to the high state the source have never returned to the low state even when its flux dropped below the detection limit of the RXTE/PCA ($\times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$).

During none of the following outbursts 2001-2003 the source flux reached the values when the transition to the high/soft state occurs (see Table 1 and Belloni et al. 2002). The 2003 outburst was observed from its first days and the source spectrum remained hard during the whole outburst.

For the spectral approximation of the data obtained during the 2003 outburst we used the comptonization model of Poutanen & Svensson (1996). The best fit parameters of the model, applied to the spectrum of XTE J1550-564 averaged over all available data are presented in Table 1. For comparison in the Table 1 we also present best fit parameters of the same model, applied to the averaged hard state spectra of XTE J1550-564 of outbursts 2000 and 2001. It is seen that the spectrum of the source during 2003 outburst is significantly harder than that of 2000 and more similar to that of 2001.

Finally we would like to note an interesting fact - every next outburst of XTE J1550-564 is weaker than the previous one (see Fig.1) and the source spectrum become harder and harder. It can be assumed that it is happening because of different physical conditions near the black hole: at the beginning of the 1998 outburst the black hole was fed by a very massive accretion disk, that was accumulated over large period of time, then with every new outburst the surface density of the accretion disk diminishes, mass accretion rate become smaller and the outbursts become weaker and harder. Applying this assumption we can predict that the next outburst will be even weaker than the last one.

Authors thank E.M.Churazov for development of the IBIS data analysis algorithms and for the supplied software. The work was supported by MINPROMNAUKI (grant of President of Russian Federation NSH-2083.2003.2) and the program of Russian Academy of Sciences ”Non stationary phenomena in astronomy”. Authors thank Integral Science Data Center (ISDC, Vesoix, Swiss) and Russian Integral Data Center (Moscow, Russia). The work is based on observations with INTEGRAL, an ESA project with instruments and science data centre funded by ESA member states (especially the PI countries: Denmark, France, Germany, Italy, Switzerland, Spain), Czech Republic and Poland, and with the participation of Russia and the USA. We have used the data obtained from Archive of High Energy Astrophysics (HEASARC) of Goddard Space Flight Center.

References

Alexandrovaich N.L., Areifev V.A., Astron.Lett. 28, 660 (2002)
Basko M., Sunyaev R., Titarchuk L., Astron. Astrophys. 31, 249 (1974)
Belloni T., Colombo A., Homan, J., et.al. Astron. Astrophys., 390, 199 (2002)
Vedrenne G., Roques J.-P., Schonfelder V., et al., Astron. Astrophys., 411, L63 (2003)
Inclination angle was fixed at $i = 73^\circ$ level. (Orosz et al. 2002)

$^a$ – Temperature of coronal electrons.

$^b$ – Optical depth.

$^c$ – Geometry factor, representing the fraction of reflected component.

$^d$ – Equivalent width of the fluorescent Fe-line.

$^e$ – Flux at 3-200 keV.

$^f$ – Flux was calculated by normalization RXTE/PCA data to the INTEGRAL/IBIS flux level.

| Outburst | $kT^a$, keV | $\tau^b$ | $R$, $\Omega/2\pi^c$ | EW$_{line}^d$, eV | Flux$^e$, erg/s/cm$^2$ | $\chi^2$/d.o.f. |
|----------|-------------|----------|---------------------|-----------------|------------------|----------------|
| 2003     | 50 ± 10     | 5 ± 1    | 0.25 ± 0.13         | 120 ± 30        | 3.8 × 10$^{-16}$ | 1.20           |
| 2001     | 63 ± 6      | 3.8 ± 0.4| 0.27 ± 0.08         | 96 ± 25         | 5.5 × 10$^{-9}$  | 1.16           |
| 2000     | 49 ± 2      | 3.3 ± 0.2| 0.7 ± 0.1           | 99 ± 20         | 2.0 × 10$^{-8}$  | 1.6            |
Fig. 1. Long term lightcurve of XTE J1550-564 in the 2-12 keV energy band according to the ASM/RXTE data.
Fig. 2. RXTE and INTEGRAL data of the XTE J1550-564 lightcurve obtained during 2003 outburst.
Fig. 3. INTEGRAL and RXTE broadband spectra of XTE J1550-564 obtained during 2003 outburst. Source spectra collected during hard state of 2000 and during 2001 outbursts are shown for comparison.