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RXTE broad band observations of X-ray Nova XTE J1755-324

M. Revnivtsev[1,3], M. Gilfanov[2,1] and E. Churazov[2,1]

[1] Space Research Institute,Russian Academy of Sciences Profsoyuznaya 84/32, 117810 Moscow, Russia
[2] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85740 Garching bei Munchen, Germany
[3] visiting Max-Plank-Insitute für Astrophysik

Abstract. The properties of X-ray Nova XTE J1755–324, observed with RXTE observatory in 1997 are reported. The lightcurve of the source was typical for X-ray Novae, except for somewhat shorter decay time scale and the time elapsed between the primary and subsequent secondary and tertiary outbursts. At the peak of the lightcurve the source had two-component spectrum, typical for the bright X-ray Novae, with a characteristic disk blackbody temperature $T_{in} \sim 0.8$ keV and a photon index of the hard power law tail $\alpha \sim 2.0$. The peak luminosity can be roughly estimated as $L \sim 10^{38}$ erg/s (0.1–100 keV, assuming 8.5 kpc distance). A notable and peculiar feature of the spectral evolution of the source was a short, ~ 10 days long, episode of increased hardness, occurred shortly before the tertiary maximum of the light curve. During the last RXTE pointed observations ~ 100 days after the primary outburst the source has been found in the hard spectral state with luminosity $\sim$few$\times 10^{36}$ erg/s. The overall pattern of the temporal and spectral evolution of XTE J1755–324 resembles in general that of "canonical" X–ray Novae (e.g. Nova Muscae 1991) and suggests that the compact object in the binary system is a black hole.

Key words: Accretion disks-Black Hole Physics-Gamma-rays:Observations-Stars:Binaries:General-X-rays:General

1. Introduction

XTE J1755–324 was discovered by All–Sky Monitor (ASM) aboard Rossi X-ray Timing Explorer (XTE) on July 25, 1997 and localized by Proportional Counter Array (PCA) at the position with coordinates R.A.=$17^h55^m28^s.6$, Dec.=$-32^\circ.28'39''$(J2000). The light curve of the source was typical for X-ray Novae (e.g. X-ray Nova Muscae 91, X-ray Nova Vulpeculae 88, see Tanaka & Shibazaki 1996 for a review) with a quick rise within a few days and an exponential decay with an e–folding time of $\sim$30–40 days. The spectrum of the source at the peak of the lightcurve was complex, with a soft component having approximately multicolor blackbody disk spectrum with $T_{in} \sim 0.8$ keV and a hard power law tail extending above 10 keV. Preliminary analysis of the data of BeppoSAX observations of the Galactic Center region in Sep. 1997 has not revealed X-ray bursts from the source (Ubertini 1997, private communication). Radio observations of the region of the sky containing the source performed on Aug 18, 1997 have not found significant radio emission from XTE J1755–324 down to ~ 0.3 mJy (Ogley, Ash & Fender 1997). The optical extinction at the direction of the source corresponding to $N_H \sim 3.7 \times 10^{21}$ cm^{-2} (Dickey & Lockman 1990) is $A_v \sim 2$, however to our knowledge no observations of the source at optical wavelengths have been reported.

2. Instruments and observations

For the analysis presented below we have used the public domain data from all three instruments aboard Rossi X-ray Timing Explorer (Bradt, Swank, Rothschild 1993) – Proportional Counter Array (PCA), High Energy X-ray Timing Experiment (HEXTE) and All Sky Monitor (ASM). The two pointed instruments PCA and HEXTE provided the

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Send offprint requests to: M. Revnivtsev broad band spectral data covering an energy range from 3 to ~ 200 keV, while the ASM data give a possibility to follow the long term behavior of the source with nearly complete time coverage.

XTE J1755–324 was observed by RXTE pointed instruments on several occasions during Summer–Fall 1997. The observations used in the analysis are listed in Table 1. The HEXTE data for the 3^{rd} observation were excluded from the analysis because of a short live time of the observation.

The data were retrieved from the XTE GOF at GSFC. The ASM light curves were used as provided by the XTE GOF. The PCA and HEXTE data were analyzed using the standard FTOOLS (version 4.1) tasks.

The latest version of the PCA background estimator (v.1.5) with the VLE (Very Large Event) based background model was used (Stark 1997). For the spectral analysis of the PCA data the version 3.3 of the PCA response matrix was used (Jahoda 1998). To roughly account for the uncertainty in the knowledge of the spectral response, a 1% systematic error was added to the statistical error in each PCA channel. The spectral data below 3 keV and above 30 keV were excluded from the analysis due to increasing systematic uncertainty in these energy ranges. The PCA dead time fraction was calculated following Zhang & Jahoda (1996). Typical values of the dead time fractions were $\sim 2.5-3.0\%$.

Table 1. The list of RXTE observations of XTE J1755–324.

	Obs.ID 20425-01-...	Date	UT start	Live time^a, s PCA	HEXTE^b
1	01	29/07/97	05:52:48	767	360
2	02-00	01/08/97	05:19:12	1993	652
3	03-00A	06/11/97	15:00:00	16	-
4	03-03S	06/11/97	15:34:02	652	735
5	04-00	12/11/97	15:38:08	3039	1673

^{a} – Deadtime corrected value
^{b} – Time for each cluster of detectors

Table 2. Parameters of spectral approximations of RXTE observations of XTE J1755–324.

Multicolor disk + power law + gaussian line (PCA data)

# Obs.	T_{in} keV	$R^a_{in} cos(\theta)^{-1/2}$, km	E^b_{line} keV	$FWHM_{line}$ keV	EW_{line} eV	F_{line} 10^{-4}phot/cm^2/s	α	$F^c_{3-30keV}$
1	0.75 ± 0.01	35.5 ± 0.7	6.4	2.92 ± 0.47	220 ± 62	14.2 ± 6.5	2.30 ± 0.34	1.72 ± 0.08
2	0.74 ± 0.01	35.7 ± 0.7	6.4	3.49 ± 0.23	418 ± 73	23.3 ± 4.0	1.83 ± 0.10	1.59 ± 0.07

Power law + gaussian line

	PCA						HEXTE	
	α	$F^c_{3-30keV}$	E_{line}	$FWHM_{line}$	EW_{line}	F_{line}	α	$F^c_{15-100keV}$
3	2.01 ± 0.06	0.49 ± 0.01						
4	1.96 ± 0.01	0.48 ± 0.01	7.00 ± 0.23	1.38 ± 0.73	126 ± 72	$3.3^{+1.80}_{-0.96}$	1.76 ± 0.15	0.29 ± 0.04
5	1.87 ± 0.01	0.40 ± 0.01	6.77 ± 0.16	1.38 ± 0.39	121 ± 36	2.7 ± 0.9	1.66 ± 0.16	0.28 ± 0.02

T_{in}, R_{in} – the temperature and the radius of the inner edge of the accretion disk in the multicolor blackbody disk model, θ – the inclination angle of the disk plane. $E_{line}, FWHM_{line}, EW_{line}$ and F_{line} – the center, the width, equivalent width and the flux of the gaussian line. α - the power law photon index; the hydrogen column density was fixed at the Galactic value $NH = 3.7 \cdot 10^{21}$ cm^{-2}.
^{a} – assuming 8.5 kpc distance
^{b} – The line energy was fixed (see text).
^{c} – in the units of 10^{-9} erg/s/cm^2.

For the spectral analysis of the HEXTE data the version 2.6 (released Mar. 20, 1997) of the response matrix was used. The background for each cluster of HEXTE detectors was estimated using the off-source observations. Only the data above 15 keV were used because of the uncertainties of the response matrix below this energy. At the high energy end the spectrum was cut at $\sim 80-150$ keV depending on the brightness of the source in order to avoid possible influence due to systematic uncertainties of the background subtraction. The deadtime correction was performed using hxtdead FTOOLS task for all observations.

3. Temporal and spectral behavior of the source.

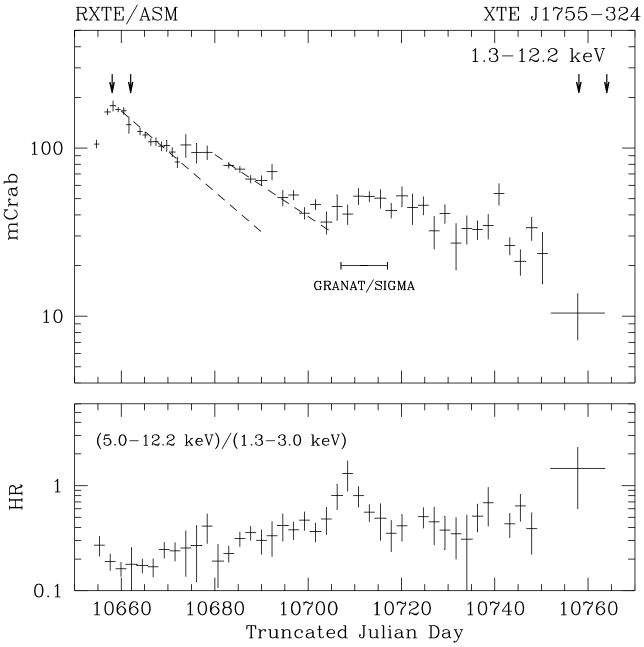

Fig. 1. The upper panel: The RXTE/ASM light curve of XTE J1755–324 in the 1.3–12.2 keV energy band. Vertical arrows mark the dates of RXTE observations, the solid horizontal line shows the dates of the GRANAT/SIGMA observations. Dashed lines show approximate fit to the light curve before and after the secondary maximum. The lower panel: The hardness ratio (5.0–12.2 keV)/(1.3–3.0 keV) derived from the XTE/ASM data. Hardness ratio ~1.0 roughly corresponds to the Crab-like spectrum.

According to the ASM/RXTE data, the light curve of the source was typical for X-ray Novae – a quick (within a few days) rise of the flux was followed by a much slower decay (Fig.1, the upper panel). Furthermore, closer examination of the shape of the light curve suggests the presence of two "kicks" around TJD 10675 and 10710 (TJD – Truncated Julian Day = JD–2440000.5) which resemble the secondary and tertiary maxima observed in the light curves of several X–ray Novae (see Tanaka & Shibazaki 1996 for a review). If these "kicks" are indeed the secondary and tertiary maxima, the XTE J1755–324 has the shortest time elapsed between the primary and the subsequent outbursts observed so far – $\sim$ 15–20 days. The e-folding decay times between the primary and the secondary maxima and after the secondary maximum are also among the shortest measured for the X-ray Novae and equal to ~ 18 and ~ 28 days respectively.

The spectrum of the source at the peak of the light curve apparently consists of two components (Fig.2, the left panel). Both July 29, 1997 and Aug 1, 1997 pointed observations show that in the standard X-ray band (3–10 keV) the emission was dominated by the soft spectral component. This soft component can be approximately fitted by a multicolor blackbody disk model (Shakura&Sunyaev 1973, Mitsuda et al. 1984) with the inner temperature $T_{in} \sim 0.77$ keV and the inner radius of the optically thick part of the accretion disk $R_{in} \sim 30 \times (cos\theta)^{-1/2}$ km (assuming 8.5 kpc distance, θ is the inclination angle of the disk plane). At energies higher than ~10 keV the power law component dominates extending to at least 30 keV with a photon index of $\alpha \sim 2.0$.

However, the χ^2 value calculated for Aug.1, 1997 data using two component multicolor blackbody disk + power law model is rather high ~ 121 (54 dof). Most prominent deviations of the data from the model are in the $\sim 5-8$ keV energy range and exceed sufficiently the present calibration uncertainties of the PCA. Addition of a broad emission line at E=6.4 keV as the third component of the model improves the quality of the fit in terms of χ^2 statistics (χ^2 ~33

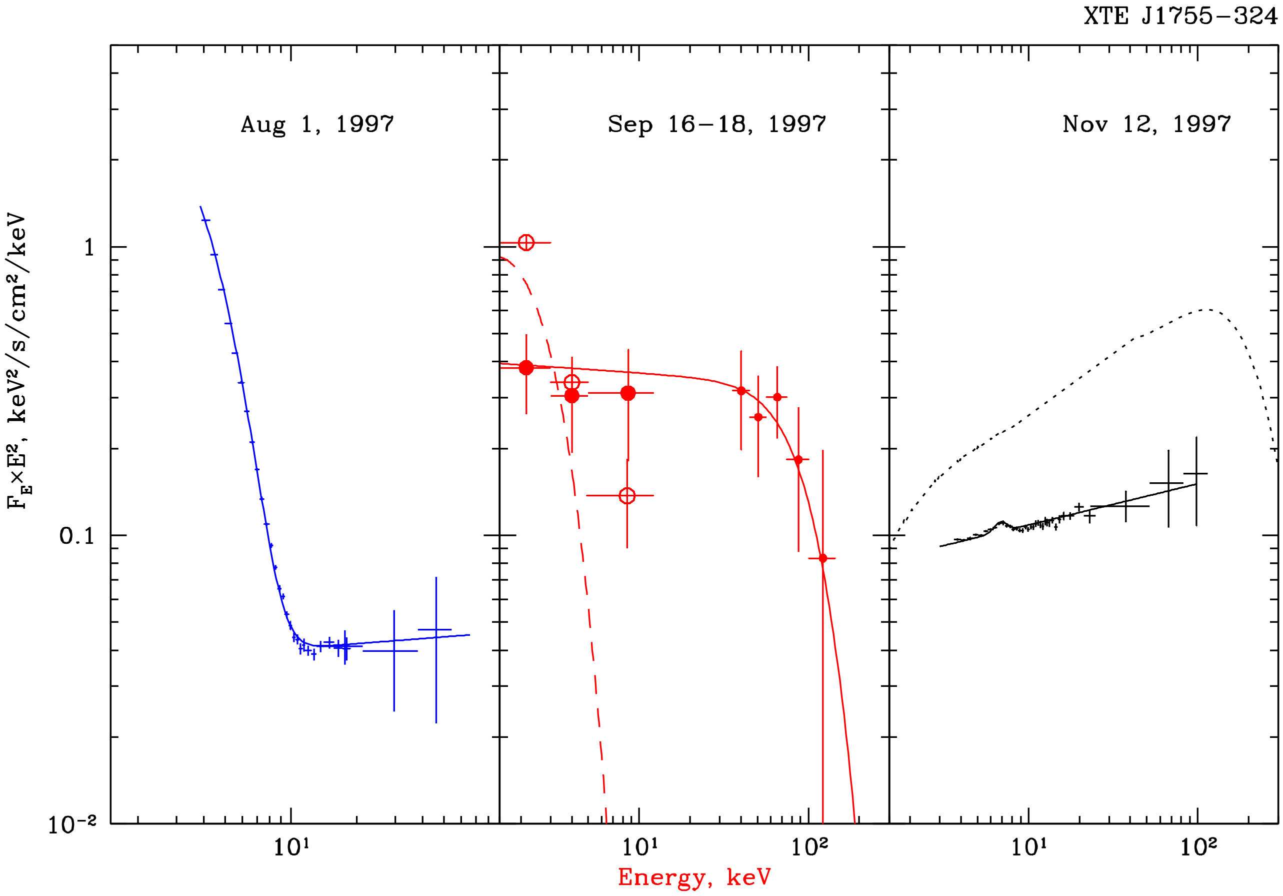

Fig. 2. Spectra of XTE J1755–324 observed at different epochs. Data in the left and right panels were obtained by PCA and HEXTE aboard RXTE, data in the middle panel were obtained by RXTE/ASM (1.3–12.2 keV) and GRANAT/SIGMA (35–150 keV, Goldoni et al. 1998, Revnivtsev et al. 1998). Open circles on the middle panel show the approximate spectrum of XTE J1755–324 just before and after the peak of the hardness (see text). Dashed line on the middle panel shows the spectrum of the soft component with R_{in} being the same as during the Aug.1, 1997 observation and T_{in}, scaled according to the luminosity change of the source. Dotted line on the right panel is the scaled spectrum of Cyg X-1 in the low spectral state. A solid line in each panel shows corresponding best fit model spectrum.

for 52 dof). The change of the central energy of the line to 6.7 keV does not affect the other parameters significantly. The line flux, 1-2$\times10^{-3}$ phot/s/cm^2, sufficiently exceeds that of the diffuse 6.7 keV line from the Galactic Ridge approximately derived from the results of GINGA observations of the Galactic Ridge (Yamauchi & Koyama 1993). However, one should bear in mind that due to complex shape of the spectrum in this energy range and sufficiently large width of the line, the line parameters depend strongly on the assumed spectral model for the continuum emission. Moreover, the line itself could be an artifact caused by inadequate continuum model. Nevertheless, we present in the Table 2 the best fit parameters for the model including the emission line.

No statistically significant flux was detected by HEXTE in the 1^{st} observation with an upper limit $F_{15-80\ keV} \lesssim 1.3\times10^{-10}$ erg/s/cm^2, (2σ). The 2^{nd} observation (longer live time) has revealed marginally statistically significant flux at the level of $\sim 1\times10^{-10}$ erg/s/cm^2 (15–80 keV, the statistical significance of $\sim 4\sigma$). The shape of the spectrum obtained by HEXTE is consistent with the extrapolation of the PCA data – the HEXTE data gives a power law photon index of $\alpha = 1.6\pm0.7$. It is worth mentioning that the source count rate detected by HEXTE ($\approx$ 2 cnt/s) was at the level of $\approx$ 1.5% of the background count rate ($\approx$ 120 cnt/s). Nevertheless, according to Rothschild et al. 1997, the systematic uncertainty of the background subtraction using the standard ftools tasks is less than $\approx$ 0.5%. We may therefore assume that the HEXTE spectrum shown on the left panel in Fig.2 is not severely contaminated by the background.

The spectrum of the source at that time was similar to the spectra of some X-ray Novae around the maximum of the light curve, e.g. X-ray Nova Vulpeculae 88 (Sunyaev et al 1988), Nova Muscae 1991 (Miyamoto et al 1991, Gilfanov et al. 1991), KS/GRS 1730–312 (Trudolyubov et al. 1996), GRS 1739–278 (Borozdin et al. 1998) except for a somewhat lower value of the photon index of the hard power law component.

No statistically significant short-term variability of the source flux was found in the PCA data with an upper limit of $\lesssim$1.5% (2σ, for 1^{st} and 2^{nd} observations , 10^{-2}–10^{2} Hz, 2–60 keV). This value is consistent with low values of rms of aperiodic flux variations usually observed in the very high spectral state of black hole binaries (e.g. Ebisawa 1991, Miyamoto et al 1991). At higher energies ($\gtrsim$15 keV), where the power law component dominates, the upper limit on the rms of the source flux variation is sufficiently large – $\sim 40\%$ (2σ) and therefore inconclusive.

The spectral evolution of the source is illustrated by the lower panel in Fig.1 where the hardness ratio derived from the ASM data is plotted. For a spectrum of the type shown in Fig.2 (the left panel) the 5.0–12.2 keV to 1.3-3.0 keV hardness ratio characterizes roughly relative contribution of the soft blackbody and the power law components. The hardness ratio increased gradually and, within the accuracy of the ASM data, sufficiently smoothly. Such a behavior was interrupted by a short episode of increased hardness around TJD 10708, lasted for $\sim 5-10$ days. At that time the hardness ratio reached ≈ 1.0, which is close to the hardness ratio of the Crab spectrum, i.e. for a power law spectrum the photon index would be ≈ 2. At the same time the Galactic Center region was observed by SIGMA telescope of GRANAT observatory and the source was detected in hard X–rays (35–75 keV) by GRANAT/SIGMA (Paul et al. 1997, Revnivtsev et al. 1998, Goldoni et al. 1998). According to the SIGMA data the power law approximation of the source spectrum above 40 keV gave a value of the photon index of ≈ 3.0. Although no spectrally resolved data below 30 keV are available, the count rate in three ASM channels can be used to derive a crude spectrum of the source. The ASM and GRANAT/SIGMA data points can be roughly described by a Comptonized cloud model with temperature kT$\sim$ 20 keV and optical depth $\tau \sim 4$. Simultaneously with the decrease of the hardness ratio observed by ASM after TJD 10708, the 35-75 keV flux decreased as well (Goldoni et al. 1998, Revnivtsev et al. 1998), and according to the ASM data the source has likely recovered the two component spectral shape with dominating soft component by TJD 10717 (Fig.2, the middle panel). The subsequent evolution of the hardness ratio is less certain because of reduced significance of the source flux, but most likely the ratio increased up to $\sim$1.0 by Nov. 1997.

This behavior was confirmed by the subsequent RXTE observations of XTE J1755–324. The spectrum obtained with PCA and HEXTE during a scan observation on Nov. 6, 1997 can be described by a power law model with a photon index $\alpha \sim 2.0$ at least up to $\sim$100 keV. Comparison of the two PCA spectra obtained on Nov.6 and Nov.12 shows that the decrease of the X–ray flux was accompanied by hardening of the power law spectrum (Table 2). The spectrum of the source obtained by PCA and HEXTE on Nov.12 is shown in Fig.2 (the right panel).

The aperiodic variability properties of the source have changed as well – the values of rms in the 10^{-2}–10^{2} Hz frequency range are $rms = 24.04 \pm 1.5\%$ on Nov.6 and $rms = 22.4 \pm 1.0\%$ on Nov.12, compared to less then 1.5% (2σ upper limit) for Aug.1, 1997 observation. The power density spectrum has a shape typical for the hard spectral state of black hole binaries (Fig.3).

An excess is clearly seen around 6-7 keV on the PCA spectrum obtained on Nov.12 (Fig.2). This feature can be adequately approximated by gaussian line at the energy 6.77 ± 0.16 keV and with the width comparable to the instrument resolution. The estimated line flux, $\sim 2.7 \times 10^{-4}$ phot/s/cm^2, is comparable with expected diffuse 6.7 keV line from the Galactic Ridge, mapped by GINGA (Yamauchi & Koyama 1993). Therefore the line flux and equivalent width given in the Table 2 should be considered as the upper limits on the intrinsic line parameters.

4. Discussion

The pattern of spectral and temporal evolutions of XTE J1755–324 bears several features in common with other X–ray Novae, e.g. X-ray Nova Vulpeculae 88 (Sunyaev et al 1988), Nova Muscae 1991 (Miyamoto et al 1991, Gilfanov et al. 1991), KS/GRS 1730–312 (Trudolyubov et al. 1996), GRS 1739–278 (Borozdin et al. 1998):

1. The shape of the X–ray light curve (short risetime, nearly exponential decay, secondary and tertiary outbursts – Fig.1) is frequently observed for X–ray Novae (Tanaka & Shibazaki 1996).
2. The two component spectrum and the low level of aperiodic variability of the X–ray flux observed at the peak of the light curve are well established features of the very high state of the black hole candidates and are often observed at the peak of the light curve of other X–ray Novae.
   The spectrum of XTE J1755–324 was dominated by the soft component which contributed more than 90% to the source luminosity. The shape of the soft component suggests that it may originates from the optically thick part of the accretion disk. Spectral fit by a simple multicolor blackbody disk model indicates that the inner radius of the optically thick disk was sufficiently close to the compact object. However, one should bear in mind that the

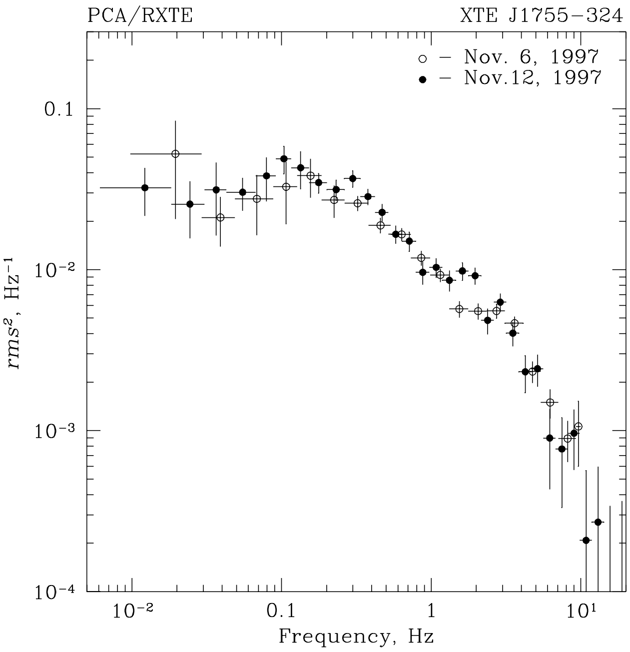

Fig. 3. Power density spectra of XTE J1755–324 in two last observations.

value of the inner disk radius derived above depends on the spectral model, the binary system inclination angle and assumed source distance.

Based on the source spectrum approximated by the two-component model consisting of a multicolor blackbody disk model and a hard power law component, the 3–30 keV luminosity near the peak of the light curve is $L_{3-30keV} \sim 1.3 \times 10^{37}$ erg/s for 8.5 kpc distance. The total absorption corrected luminosity of the source in the 0.1–25.0 keV energy band can be estimated as $L_{0.1-25keV} \sim 1 \times 10^{38}$ erg/s. This value is close to the luminosity of other black hole candidates in the very high state, which might indicate that the assumption about the source distance is roughly correct.

3. Anticorrelated behavior of the X–ray flux and the 5.0–12.2 keV to 1.3-3.0 keV hardness ratio before and during some time after the primary outburst (Fig.1, the bottom panel).

   The hardness ratio plot shows that the spectrum of XTE J1755–324 softened during the initial rise of the flux. Similar behavior was observed for other X-ray Novae – GRS/GS 1124–64 (Nova Muscae 1991, Miyamoto et al 1991), KS/GRS 1730–312 (Trudolyubov et al. 1996), GRS 1739–278 (Borozdin et al. 1998), and is likely due to the increase of the relative contribution and the absolute luminosity of the soft spectral component caused by increase of the mass accretion rate and corresponding increase of the disk temperature.

   After the peak of the light curve the hardness ratio increased gradually and fairly smoothly with a brief excursion around TJD 10708. The gradual increase of the hardness ratio after the primary outburst is also seen in the spectral evolution of other X–ray Novae. Although no spectrally resolved data is available in the case of XTE J1755–324, we may suppose that it is related to decrease of the mass accretion rate and corresponding decrease of the disk temperature (that is usually followed by a transition to the low spectral state).

4. Transition to the low spectral state during decay.

   The transition of the source to the low spectral state itself was not traced by the pointed instruments aboard RXTE, but during November 1997 observations the source has been found in the low spectral state according to both spectral (Fig.2, the right panel) and aperiodic variability (Fig.3) properties. The 4-100 keV luminosity was $L_{4-100keV} \sim 5 \times 10^{36}$ erg/s (Nov. 12, 1997, PCA and HEXTE data, the HEXTE normalization was adjusted to that of PCA).

A notable and apparently peculiar feature of the source evolution was a brief excursion seen on the hardness ratio plot (Fig.1) around TJD 10708. Comparison of July-Aug. 1997 and Sep. 1997 spectra of XTE J1755–324 observed with RXTE/HEXTE and GRANAT/SIGMA (Paul et. al 1997) in the high energy domain further confirms a fact of strong spectral evolution (see Fig.2). The RXTE/HEXTE observation near the peak of the light curve on Aug. 1, 1997 gave the hard X–ray flux $F_{40-75keV} \sim 9 \times 10^{-11}$ ergs/s/cm^2. The relative contribution of the hard power law component to the total flux in the 3–30 keV energy band was at the level of ∼10%. The hard X-ray flux from the source measured by GRANAT/SIGMA near the peak of the hardness is $F_{40-75keV} \approx 5 \times 10^{-10}$ ergs/s/cm^2 (Paul et al. 1997), i.e. the 40–75 keV flux from the source increased by a factor of ∼5. At the same time according to RXTE/ASM data the 1–12 keV flux decreased by a factor of ∼4–5 (Fig.1). Obviously the observed spectral changes can not be accounted for in terms of a simple scaling of the soft spectral component according to the luminosity change (see p.3 above). Moreover, comparison of the ASM spectra obtained before/after and during this event (Fig.2, the middle panel) shows clearly, that not only luminosity in the high energy band increased but also the luminosity below $\sim$ 5 keV decreased by a factor of $\sim 2-3$. No evidence of the soft spectral component of the type observed just before and immediately after the event is seen in the ASM data taken at the peak of hardness.

Assuming a power law spectrum with a photon index $\alpha = 2.0$ and a high energy cutoff (Comptonization spectrum with kT∼ 20 keV and $\tau \sim 4$) which roughly describes ASM and SIGMA data in the 1-150 keV range, (solid line in the middle panel in Fig.2) the 1.3–150 keV luminosity is $\sim 2 \times 10^{37}$ erg/s, which is close to typical low spectral state luminosity of Cyg X-1 and 1E1740.7–2942 (e.g. Sunyaev & Truemper 1979, Sunyaev et. al 1991). In general, the shape of the spectrum, observed with RXTE/ASM and GRANAT/SIGMA in the middle of September 1997 is typical for the low state of the black hole binaries except for the noticeably lower value of the Comptonization temperature. A possible explanation of the event might be that it is due to a spectral transition to the hard state followed by a transition back to the soft state caused by an increase of the mass accretion rate corresponding to the tertiary maximum of the light curve. Such an event can occur when the accretion rate is near a critical level: e.g. a hard-soft-hard transition in Cyg X–1 (Zhang et al., 1997). Crucial data for understanding the nature of the event might be the timing information which unfortunately is absent – no pointed observations were performed by RXTE at that time.

The pattern of the spectral and temporal evolution of XTE J1755–324 is similar to that of “canonical” X–ray Novae of dynamically proven black hole candidates and suggests that the binary system XTE J1755–324 also harbors a black hole.

5. Acknowledgments

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