SIGMA AND RXTE OBSERVATIONS OF THE SOFT X-RAY TRANSIENT XTE J1755−324

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ABSTRACT

We present observations of the X-ray transient XTE J1755−324 performed during 1997 summer with the Rossi X-Ray Timing Explorer (RXTE) satellite and with the SIGMA hard X-ray telescope on board the GRANAT observatory. The source was first detected in soft X-rays with RXTE on 1997 July 25 with a rather soft X-ray spectrum, and its outburst was monitored in soft X-rays up to 1997 November. On September 16 it was first detected in hard X-rays by the French soft γ-ray telescope SIGMA during a Galactic center observation. The flux was stronger on September 16 and 17, reaching a level of ~110 mcrab in the 40–80 keV energy band. On the same days, the photon index of the spectrum was determined to be $\alpha = -2.3 \pm 0.9$ (1 σ error), while the 40–150 keV luminosity was $\sim 8 \times 10^{36}$ ergs s$^{-1}$ for a distance of 8.5 kpc. SIGMA and RXTE results indicate that this source had an ultrasoft-like state during its main outburst and a harder secondary outburst in September. These characteristics make the source similar to Nova Muscae 1991, a well known black hole candidate.

Subject headings: black hole physics — gamma rays: observations — novae, cataclysmic variables — X-rays: bursts

1. INTRODUCTION

The X-ray transient XTE J1755−324 was discovered by the Rossi X-Ray Timing Explorer (RXTE) All-Sky Monitor (ASM) on 1997 July 25 (Remillard et al. 1997) in the Galactic center region. On July 29, it was observed with two pointed instruments, the Proportional Counter Array (PCA, sensitive in the 2–30 keV energy band) and the High-Energy X-Ray Timing Experiment (HEXTE, sensitive in the 20–100 keV band), and its precise position was determined to be R.A. $17^h52^m12^s$, decl. $-32\deg 28'12''$ (B1950, uncertainty 1'), while its flux was 170 mcrab in the 2–12 keV band (1 mcrab in the 2–12 keV band corresponds to $4.3 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$). The observed PCA spectrum was fitted with a multicolor disk blackbody with $T \sim 0.7$ keV, and a hard tail extending up to 20 keV (Remillard et al. 1997).

The outburst of XTE J1755−324 was followed by the RXTE/ASM in the 2–12 keV energy band in the following months. After the initial fast rise, the source flux decayed in an exponential way, and the source was detected up to the end of November. During the entire observed outburst no type I X-ray burst or pulsation, the most certain observational signatures of neutron stars, were reported from this source (P. Ubertini 1998, private communication). This light curve resembles that of well-known X-ray novae such as Nova Muscae 1991 (Ebisawa et al. 1994), which is also a good black hole candidate on the basis of its mass function (Mc Clintock et al. 1992; Orosz et al. 1996). No optical counterpart has been proposed for XTE J1755−324, while a radio search performed on 1997 August 17–18 with the Australia Telescope Compact Array (Ogley et al. 1997) gave no detection up to a limit of 0.2 mJy (1384 MHz) and 0.3 mJy (2496 MHz).

We have carried out archival searches in the RXTE 1 error box in the ROSAT All-Sky Survey Bright Source Catalog, and we obtained no detection, resulting in an upper limit of 0.05 ROSAT/PSPC counts s$^{-1}$ for the source quiescent emission. This translates into a 0.1–2.4 keV upper limit of $\sim 7 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$, assuming a Crab-like spectrum and a $10^{32}$ cm$^{-2}$ absorption column density.

2. SIGMA OBSERVATIONS AND RESULTS

The French coded mask telescope SIGMA on board the Russian GRANAT observatory provides high-resolution images in the hard X-ray/soft γ-ray band from 35 to 1300 keV, with a typical angular resolution of 15' and a 20 hr exposure sensitivity (1 σ) of ~20 mcrab in the 40–150 keV band (Paul et al. 1991). (1 mcrab corresponds to $8.0 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$ in the 40–80 keV energy band, and $6.9 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$ in the 80–150 keV energy band). The position determination accuracy of the instrument can be 3′−5′ for a 6 σ source and < 1′ for a 30 σ source. The fully coded field of view (FCFOV) of the instrument is a 4′7 × 4′3 rectangle, while the extended field of view (EXFOV) is a larger rectangle, 18′.1 × 16′.8.

The 1997 fall Galactic center campaign began 1997 September 16 (MJD 50707), 52 days after the discovery of XTE J1755−324 (MJD 50655). A hard X-ray source was localized by SIGMA during the first observing session with 6' accuracy (90% error circle) at R.A. = $17^h52^m21^s$, decl. = $-32\deg 27'02''$ (B1950), about 2′ from the RXTE position stated above and slightly outside the fully coded FOV (Paul et al. 1997). The SIGMA telescope continued its observations of the Galactic center for a total of five observations and about 123 hr of effective observing time.

During the campaign, the hard X-ray flux of XTE J1755−324 declined (see Table 1 and Fig. 1), passing from ~110 mcrab to 39 mcrab in the 40–80 keV energy band. We thus analyzed in more detail the results of the first
observation, which took place between September 16 and 18, when the source was stronger. As can be seen in Table 1 and Figure 1, the source flux was stronger during the first half of this observation (September 16–17).

To better illustrate this fact, in Figure 2 we show two 40–80 keV images of a 6.5' × 6.5' region of the Galactic center containing XTE J1755−324 and also 1E1740.7-2942, which was less variable during the entire campaign. The image on the left is a sum of the first half of the first observation; the second image is a sum of the second half. It appears that XTE J1755−324 was the strongest source in the field during the first part of the observation, appearing as a ~6 σ source with a mean flux of about 110 mcrab in the 40–80 keV energy band and 80 mcrab in the 40–150 keV energy band (see Table 1). The hard X-ray outburst, however, ended quickly, and in the second half of this observation the source was below the 4 σ level (Fig. 2, right panel).

In order to have the smallest errors, we extracted a spectrum of XTE J1755−324 from the first half of the first observation. The result is shown in Figure 5; the source is clearly detected up to ~150 keV. We fitted the resulting spectrum with a power law, our best fit being obtained with a photon index $\alpha = -2.3 \pm 0.9$ and a 40–150 keV energy flux of $I(\pm 0.2) \times 10^{-9}$ ergs cm$^{-2}$ s$^{-1}$.

The source luminosity was $L_X$ (40–150 keV) $\approx 8 \times 10^{36}$ ergs s$^{-1}$, assuming a distance of 8.5 kpc. To make a comparison, Nova Muscae 1991 and Nova Velorum 1993 had 40–150 keV luminosities $L_X \approx 10^{35}$–$10^{36}$ ergs s$^{-1}$, respectively, 100 and 120 days after their main outbursts (Goldwurm et al. 1993; Gilfanov et al. 1991; Goldoni et al. 1998).

To investigate the possibility of previous activity from the source, we reanalyzed the SIGMA database of Galactic center observations. The SIGMA telescope monitored this sky region from 1990 to 1997, making regular observations lasting about 0.5–1 month two times a year. We summed the images of all these observations and searched for excess flux at the source position. We did not detect any significant signal, and we obtained a $2 \sigma$ upper limit of ~3 mcrab in the 40–150 keV energy band.

3. RXTE OBSERVATIONS AND RESULTS

After its discovery, XTE J1755−324 was observed by the pointed instruments PCA and HEXTE on 1997 July 29 and was monitored by the ASM during all of its outburst.

We reanalyzed the public data of the pointed observations of July 29 and found results compatible with those quoted by Remillard et al. (1997) (see also Revnivtsev et al. 1998). XTE J1755−324 was clearly detected in the 2–20 keV energy band, and its emission could be fitted with a blackbody or a multicolor disk blackbody (Makishima et al. 1986) with $kT \approx 0.7$–0.8 keV and an inner radius of the blackbody region $R_{in} \approx 36 \times (\cos \theta)^{-1/2}$ km (assuming 8.5 kpc distance), plus a power law extending up to about 20 keV, with photon index $\alpha \approx -2$ (Fig. 3). We estimated a best-fit hydrogen absorption column density of $\sim 1.5 \times 10^{22}$ cm$^{-2}$. The source was not detected with HEXTE, and we estimated a conservative 40–150 keV upper limit of $F_X(40–150$ keV) $\leq 8 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$, assuming a power-law spectrum with $\alpha \approx -2$. The 2–20 keV luminosity of the source was about $2 \times 10^{37}$ ergs s$^{-1}$ at 8.5 kpc distance. This spectrum, characterized by an “ultrasoft” component ($kT \leq 1$ keV) and a power law starting at about 10 keV, was observed in several X-ray novae, such as Nova Muscae 1991 (Ebisawa et al. 1994) and A0620-00 (Ricketts et al. 1975), at the beginning of their outbursts. We also note that the upper limit on the hard X-ray flux is about 10–15 times lower than the flux recorded

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**TABLE 1**

| Session | Date (1997) | Exposure (hr) | 40–80 keV Flux (mcrab) | 80–150 keV Flux (mcrab) | 40–150 keV Flux (mcrab) |
|---------|-------------|---------------|------------------------|------------------------|------------------------|
| 1.I      | Sep 16.4-17.3 | 14.7 | 114 ± 26 | 61 ± 30 | 83 ± 20 |
| 1.II     | Sep 17.3-18.2 | 14.7 | 64 ± 26 | <30 | 19 ± 20 |
| 1.I + II | Sep 16.4-18.2 | 29.2 | 84 ± 19 | 22 ± 21 | 48 ± 15 |
| 2         | Sep 18.7-20.2 | 24.4 | 68 ± 21 | 39 ± 22 | 51 ± 16 |
| 3         | Sep 20.3-22.2 | 14.7 | 28 ± 27 | <30 | 2 ± 21 |
| 4         | Sep 22.8-24.2 | 22.7 | 28 ± 22 | 41 ± 24 | 36 ± 16 |
| 5         | Sep 24.3-26.3 | 31.7 | 39 ± 18 | 5.5 ± 20 | 19 ± 14 |
| Sum       | Sep 16.4-26.3 | 122.7 | 53 ± 9 | 21 ± 10 | 34 ± 7 |

**Note:** Errors quoted are at the 68% confidence level in one parameter. Upper limit is at 68% confidence level. The fluxes of each observing session are presented, while the first observing session has been divided in two.
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by SIGMA on September 16–17, thus showing a strong rise between the two observations.

Further information is provided by the RXTE/ASM source light curve in the 1.3–12.2 keV energy band. This light curve is shown in Figure 4 (upper panel); the count rate to energy conversion is based on the rule that \( \sim 75 \) ASM counts s\(^{-1}\) are equal to 1 crab in the 1.3–12.2 keV band. The lower panel of Figure 4 plots the ratio between the 5.0–12.2 keV and the 1.3–3.0 keV flux; this parameter roughly indicates the spectral shape in this band, hardness ratios of 0.1 and 1.0 roughly corresponding to photon indices of 4.0 and 2.0, respectively. In both graphics the plots were produced using the FTOOLS task LCURVE, with a bin length of 3 days. In the lower graph, three points are not represented, since the 5.0–12.2 keV recorded flux was less than zero, while in some others only upper limits are available.

Overall, the source light curve has a typical fast rise/exponential decay (FRED) shape, with some interesting features. As is shown by superimposed log-linear fits, the exponential decay is probably interrupted a first time around MJD 50680, i.e., \( \sim 20 \) days after the outburst, and then continues with a similar decay constant but with a slightly higher intensity. This behavior has been referred to as a “glitch,” and it has been seen in X-ray light curves of GRO J0422+32, A0620-00, and GRS 1124-68 (Chen, Shrader, & Livio 1997). The decay constants before and after the proposed glitch are \( \sim 24 \pm 12 \) and \( \sim 32 \pm 20 \) days, and are thus compatible.

A larger feature appears around MJD \( \sim 50705 \), where

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**Figure 4:** Upper panel: 1.3–12.2 keV RXTE All-Sky Monitor light curve of XTE J1755—324. The horizontal line marks the epoch of SIGMA observations. The dashed lines show linear fits before and after the probable secondary maximum. Lower panel: RXTE/ASM hardness ratio (5.0–12.2 keV)/(1.3–3.0 keV) light curve. The hardness ratio increases at the beginning of SIGMA observations, reaching a value of about 0.6, which roughly corresponds to a photon index 2.5. Some points are missing in the lower panel because of insufficient statistics.
Fig. 5.—1–150 keV SIGMA/RXTE spectrum of XTE J1755−324 taken on 1997 September 16 is shown together with a plot of the 1997 July 29 PCA/HEXTE spectrum. Filled circles are SIGMA data, crosses are ASM data. The dotted line shows the best-fit power-law spectrum obtained from SIGMA data; one can see that this spectrum is also compatible with the RXTE/ASM data. The dashed line represents the source spectrum detected on 1997 July 29; the long upper limit shows the HEXTE nondetection. It is apparent that the spectral shape was different at these two dates (see text for details).

there is a clearly visible stop in the flux decay and a possible flux rise that lasts up to MJD \( \sim 50725 \). After this event the source restarts its decline, going under 20 mcrab at the end of November (MJD \( \sim 50780 \)). This type of event has been defined as a “bump,” and it has been seen in X-rays in A0620-00 and GRS 1124-68 (Chen et al. 1997). We note that SIGMA observation were performed during the bump on September 16–18 (MJD 50708-50710). Moreover, the ASM hardness ratio shows evidence of a spectral hardening in the 1.3–12.2 keV band at the same time (see Fig. 4, lower panel). In fact, the average hardness ratio of the source in the period from MJD 10655 to MJD 10706 was \( <HR> = 0.14 \pm 0.06 \), while in the days from MJD 10706 to MJD 10712 it was \( <HR> = 0.6 \pm 0.2 \). The implied photon index evolves from \( \sim 4 \) to \( \sim 2.5 \), indicating a rise in the flux at \( E > 5 \) keV.

In Figure 5 we plot the 1–150 keV ASM/SIGMA spectrum of XTE J1755−324 on September 16, along with the SIGMA spectral fit. It can be seen that this entire spectrum is compatible with a single power law with photon index \( \alpha \sim 2.3 \), and that no strong ultrasoft excess is present. However, we cannot rule out the presence of a weak soft excess at low energies, which could be easily masked by the strong hard component. In any case, on that date the 2–12 keV X-ray flux was about 40 mcrab, 4 times lower than at outburst peak, while, as seen before, the 40–150 keV X-ray flux was 10–15 times stronger than on July 29. One possible interpretation of this behavior is that a soft-to-hard state transition similar to the ones that occur in the well-known black hole candidate Cyg X-1 took place between the two observations. We must remark, however, that our data also allow for the existence of a weak ultrasoft component, so no firm conclusion can be made on this point.

4. DISCUSSION

XTE J1755−324 is an X-ray transient that displayed spectral evolution in detections at different epochs by RXTE and GRANAT/SIGMA. We will show in the following discussion that the evidence points toward a classification of this source as an X-ray nova of the type of Nova Muscae 1991.

The outburst light curve recorded by RXTE/ASM is characterized by a fast rise (2–3 days) and an exponential decay with a timescale of about 20–30 days, with a possible secondary outburst \( \sim 20 \) days after the primary outburst and a strong bump after about 45 days. This behavior has been observed in Nova Muscae 1991 and A0620-00 in the standard (1–10 keV) X-ray band (see, e.g., Chen et al. 1997). The spectrum at the outburst peak could be fitted with a multicolor disk blackbody or a blackbody with \( kT \lesssim 1 \) keV and a power-law component that is again typical of these sources (Tanaka & Shibazaki 1996). In our hypothesis, the source was then in a typical ultrasoft state, which is frequently recorded during first phases of X-ray novae outbursts.

The hard X-ray flux was rather faint at outburst peak, while it was \( \sim 10–15 \) times stronger on September 16, decaying in the following days. In the meantime, the 2–12 keV emission was undergoing a rather long secondary outburst or bump whose evolution was apparently uncorrelated with the hard X-ray evolution. The hard X-ray spectral index recorded on September 16–17 was \( \alpha \sim 2.3 \pm 0.9 \), and the source was detected above 100 keV. As shown in Figure 5, ASM and SIGMA data recorded on this date are compatible with the hypothesis of a 1–150 keV spectrum described by a single power law with \( \alpha \sim 2.3 \). Moreover, the ASM (5.0–12.2)/(1.3–3.0) keV hardness ratio on that day indicates that the soft X-ray spectrum was harder than during the outburst maximum; its value indicates a spectrum with a photon index of \( \sim 2.5 \). The errors in our spectra are too large to determine a spectral index typical of a low (i.e., \( \alpha \sim 2 \)) or high (\( \alpha \sim 3 \)) state. In any case, the wide-band spectral shape suggests that the source either had a weak ultrasoft component not detectable in our data or was in a spectral state analogous to the low state of black hole candidates such as Cyg X-1. An analysis of short-term variability behavior would secure the identification of the spectral state of the source; unfortunately, the source is too faint for timing analysis in SIGMA data, while ASM data points do not have the necessary timing resolution.

This behavior, characterized by a strong ultrasoft component at the beginning of the outburst followed by a strong rise of the hard X-ray part of the spectrum, has been detected in the outburst of Nova Muscae 1991 (see, e.g., Kitamoto et al. 1992; Ebisawa et al. 1994; Goldwurm et al. 1993). The X-ray nova GRS 1009-45 also displayed this behavior (Sunyaev et al. 1994; Goldoni et al. 1998). This behavior can be naturally explained in bulk-flow Comptonization models (Titarchuk, Mastichiadis, & Kylafis 1997; Laurent & Titarchuk 1998) as the result of changes in mass accretion rate. In this scenario, the high-mass accretion rates that occur during the primary outburst produce a strong soft X-ray flux that efficiently cools down the Compton cloud around the disk. The Compton cloud then becomes transparent to soft X-radiation, and no thermal Comptonization emission is visible. The hard X-ray emission in this case is due to bulk motion Comptonization occurring closer to the black hole, which produces a spectral index \( \sim 2.8 \) (Laurent & Titarchuk 1998). In the context of these models, the presence of the extended power
law together with the ultrasoft component is considered to be a black hole signature. In our interpretation, this is the spectral state that was observed by RXTE on July 29. Later in the outburst, however, the mass accretion rate is lower and the optical depth of the Compton cloud increases, thus causing the appearance of the typical thermal Comptonization spectrum, which can be modeled with a power law with a spectral index of $\sim -2$ in the energy range 1–150 keV, compatible with the spectrum observed by SIGMA and RXTE on September 16. In our case, however, a weak ultrasoft component was possibly present together with the power law component, and we cannot be sure of the origin of the emission on that date.

Unfortunately, without an optical or radio counterpart we do not have precise information on the source distance. The absorption column density we estimated from RXTE/PCA observations is strongly dependent on the spectrum. A possible distance estimate can be made from our hypothesis that the source is an X-ray nova; in that case its outburst luminosity can be estimated to be near the Eddington luminosity in the standard X-ray band (Chen et al. 1997). Taking into account the absorption column density we quoted and the relatively low flux at maximum, we tentatively suggest that the source is in the Galactic bulge. If this is the case, it would be the fourth faint ($F_{\text{max}} < 1$ crab) Galactic bulge X-ray transient detected by SIGMA after GRS 1737-31 (Trudolyubov et al. 1998; Cui et al. 1997), GRS 1730-312 (Vargas et al. 1996; Trudolyubov et al. 1997), and GRS 1739-278 (Vargas et al. 1997).

5. CONCLUSION

We reported on the hard X-ray detection of XTE J1755—324 with the SIGMA telescope. The general characteristics of its light curve and its spectrum characterize it as an X-ray nova. The soft X-ray light curve with a fast rise and an exponential decay is typical of black hole candidates such as X-ray Nova Muscae 1991 (Ebisawa et al. 1994) and A0620-00 (Ricketts et al. 1975). Its spectrum was dominated by an ultrasoft ($kT \lesssim 1$ keV) component during the primary outburst and by a power law extending up to more than 100 keV during SIGMA September observations 50 days after the primary outburst. The general behavior of the source during the outburst, together with the absence of type I X-ray bursts and pulsations, lead us to suggest that this source is a black hole candidate that is likely in the Galactic bulge, as are the other three faint transient sources detected by SIGMA.

This class of sources is a natural target for SIGMA, thanks to its localization accuracy, unprecedented in this energy band. It has been proposed (Vargas et al. 1997), on the basis mainly of SIGMA data, that these transients reach a peak luminosity of $\sim 10^{37}$ erg s$^{-1}$ in the hard X-ray band. This would mean that, with its limited sensitivity, SIGMA can detect these transients only in a limited region of our galaxy, i.e., up to about 10 kpc. To detect more transients of this type, more sensitive instruments are needed.

The IBIS (Imager on Board Integral Satellite) coded mask telescope (Ubertini et al. 1997) has a predicted 40–150 keV sensitivity at the 3σ level of about 3.5 mcrab in a 1 day observation. IBIS will thus be able to detect flaring transients at distances up to 30 kpc (peak flux about 12 mcrab for a $10^{37}$ ergs s$^{-1}$ luminosity), i.e., in the entire Galaxy. Thanks to IBIS source localization capability and the low absorption in this energy band, it will be possible to make a reliable experimental census of all the hard X-ray novae in the Galaxy.

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REFERENCES

Chen, W., Shrader, C. R., & Livio, M. 1997, ApJ 491, 312
Cui, W., et al. 1997, ApJ, 487, L73
Ebisawa, K., et al. 1994, PASJ, 46, 375
Gilfanov, M., et al. 1991, Soviet Astron. Lett., 17, 1059
Goldoni, P., et al. 1998, A&A, 329, 186
Goldwurm, A., et al. 1993, A&AS, 97, 293
Kitamoto, S., et al. 1992, ApJ, 394, 609
Laurent, P., & Titarchuk, L. 1998, ApJ, in press
Massicherida, A., et al. 1986, ApJ, 308, 635
Mc Clintock, J. E., et al. 1992, IAU Circ. 5499
Ogley, R. N., et al. 1997, IAU Circ. 6726
Orosz, J., et al. 1996, ApJ, 468, 380
Paul, J., et al. 1991, Adv. Space Res., 11(8), 289
________. 1997, IAU Circ. 6746
Remillard, R., et al. 1997, IAU Circ. 6710
Revnivtsev, M., et al. 1998, A&A, submitted
Ricketts, M. J., et al. 1997, Nature, 257, 657
Sunyaev, R., et al. 1994, Astron. Lett., 20, 777
Tanaka, Y., & Shibazaki, N. 1996, ARA&A, 34, 607
Titarchuk, L., Mastichiadis, A., & Kylafis N. D. 1997, ApJ, 487, 834
Trudolyubov, S., et al. 1997, Pisma Astron. Zh., 22, 740
________. 1998, in preparation
Ubertini, P., et al. 1997, Proc. 2nd INTEGRAL Workshop, The Transpar- ent Universe, ed. C. Winkler, T. J-L. Courvoisier, & Ph. Durouchoux
(Noordwijk: ESA)
Vargas, M., et al. 1996, A&A, 313, 828
________. 1997, ApJ, 476, L23