A&A manuscript no.
(will be inserted by hand later)

Your thesaurus codes are:
08 (01.01.2; 02.02.1; 13.07.2; 08.02.3)

ASTRONOMY AND ASTROPHYSICS
September 29, 2000

RXTE observations of XTE J2012+381 during its 1998 outburst.

L. Vasiliev[1], **S. Trudolyubov**[2,1], **M. Revnivtsev**[1,3]

[1] Space Research Institute, Russian Academy of Sciences Profsoyuznaya 84/32, 117810 Moscow, Russia
[2] Los Alamos National Laboratory, Los Alamos, 87545 New Mexico, USA
[3] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85740 Garching bei Munchen, Germany

Abstract. We present an analysis of the *RXTE* observations of X-ray transient source XTE J2012+381 during its 1998 outburst. The spectral and timing properties of the source emission and their evolution during the outburst are very similar to those of the X-ray Novae that have been associated with black hole candidates.

Key words: stars: binaries: general – stars: individual: XTE J2012+381 – X-rays: stars

1. Introduction

The XTE J2012+381 was discovered as a new transient source on May 27, 1998 by All Sky Monitor (ASM) aboard the Rossi X-ray Timing Explorer, *RXTE* (Bradt, Swank & Rothschild 1993) observatory (Remillard et al. 1998). The X-ray source was localized with an accuracy of 1 arcmin in multiple scans of the region by PCA/*RXTE* experiment (Marshall & Strohmayer 1998): $R.A. = 20^h12^m43^s, Dec = 38°11.0'$ (equinox 2000.0). Observations in the optical band by 1.0-m Jacobus Kapteyn Telescope showed the presence of a possible optical counterpart USNO 1275.13846761 : $R.A. = 20^h12^m37.8^s, Dec = +38°11'00.6''$ (equinox 2000.0)(Hynes & Roche 1998). Observations in the radio band by the VLA revealed the presence of the likely counterpart of XTE J2012+381: $R.A. = 20^h12^m37.67, Dec = +38°11'01.2''$ (equinox 2000.0, uncertainty 0.5″) as well. Significant variability of the new radio source supports its association with the X-ray transient (Hjellming et al. 1998, Pooley 1998). From early observations of this transient it was assumed to be black hole candidate (e.g. White et al 1998).

The pointed instruments of *RXTE* – PCA and HEXTE observed the source quasi evenly from May to July 1998, providing good coverage of the whole outburst. The flux from the source was above the ASM/*RXTE* detection limit until December 2, 1998. In this Letter we present the results of a spectral and timing analysis of *RXTE* pointed observations.

Send offprint requests to: leonid@hea.iki.rssi.ru

Table 1. The list of *RXTE*/PCA observations of XTE J2012+381 used for the analysis.

Obs.ID	Time start			Exp.[a], s
	Date	Time, UT	TJD	
30188-04-01-04S[b]	27/05/98	16:21	10960.7	78
30188-04-02-00	29/05/98	17:48	10962.7	3195
30188-04-03-00	30/05/98	19:25	10963.8	6002
30188-04-04-00	31/05/98	21:41	10964.9	2712
30188-04-05-00	01/06/98	17:47	10965.7	6002
30188-04-06-00	02/06/98	21:41	10966.9	780
30188-04-07-00	03/06/98	18:28	10967.8	779
30188-04-08-00	04/06/98	21:50	10968.9	219
30188-04-09-00	05/06/98	22:43	10970.0	843
30188-04-10-00	07/06/98	01:52	10971.1	2904
30188-04-11-00	07/06/98	19:25	10971.8	3017
30188-04-12-00	08/06/98	19:24	10972.8	3156
30188-04-13-00	09/06/98	21:03	10973.8	2940
30188-04-14-00	11/06/98	00:18	10975.0	2765
30188-04-15-00	15/06/98	00:24	10979.0	2400
30188-04-16-00	16/06/98	17:46	10980.7	1532
30188-04-17-00	22/06/98	21:29	10986.9	1527
30188-04-18-00	30/06/98	21:29	10994.9	865
30188-04-19-00	30/06/98	23:12	10994.9	699
30188-04-20-00	06/07/98	18:04	11000.7	1300
30188-04-21-00	13/07/98	00:52	11007.0	1625
30188-04-22-00	19/07/98	18:07	11013.8	2783
30188-04-23-00	21/07/98	21:26	11015.9	2317
30188-04-24-00	29/07/98	18:40	11023.8	736

[a] – Deadtime corrected value of the PCA exposure
[b] – Slew part of observation

2. Observations and data analysis

In our analysis we used all the publicly available data obtained from *RXTE* archive including 24 pointed observations. The 24 observations quasi evenly cover the 1998 outburst of the source with a total exposure of ∼ 46 ks. The list of observations is presented in Table 1.

For data reduction we used the standard FTOOLS package version 5.0 For the spectral analysis we used PCA data collected in the 3-20 keV energy range. The response matrix was constructed for every observation using pcarmf

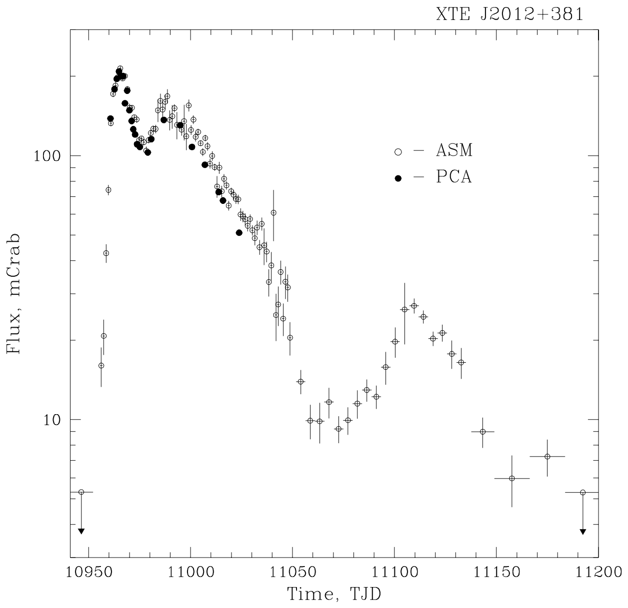

Fig. 1. Light curve of the 1998 outburst of the X-ray transient XTE J2012+381. Open circles and filled circles represent the data of All Sky Monitor (ASM/*RXTE*, 1.3 – 12.2 keV) and Proportional Counter Array (PCA/*RXTE*, 3 – 20 keV) respectively.

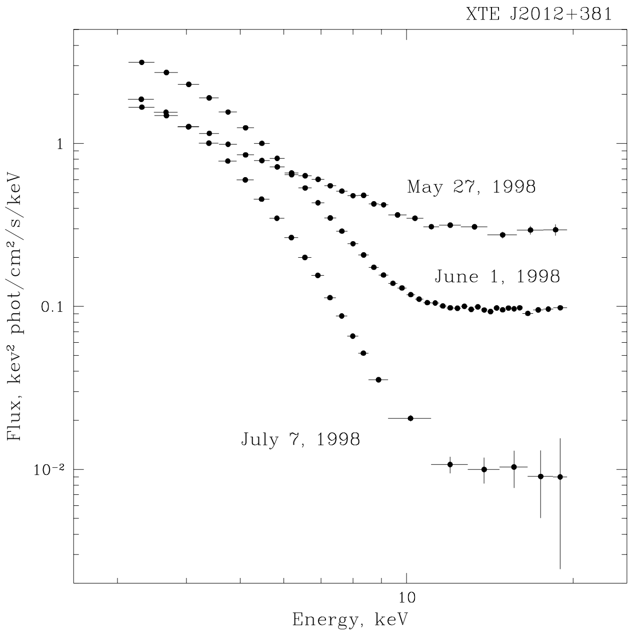

Fig. 2. Typical energy spectra of XTE J2012+381 during 3 consequent phases. One can see that the strength of the soft component rises while the strength of the power law component decreases.

v3.5. For the PCA background subtraction we applied a Very Large Events (VLE)-based model. The standard dead time correction procedure was applied to the PCA data. In order to account for the uncertainties of the response matrix, a 1% systematic error was added to the statistical error for each PCA energy channel.

HEXTE data reduction was done with FTOOLS 5.0 standard tasks and according to RXTE GOF recommendations.

We generated an averaged energy spectgrum of XTE J2012+381 for each of the 24 observations. The spectral data were approximated with the simplest two-component model: the sum of the XSPEC "multicolor disk black body" (Mitsuda et al. 1984) and a simple power law model with inclusion of a broad gaussian emission line at 6.4 keV. The results of the spectral approximation of the PCA data with analytical models described above are presented in Table 2.

For the timing analysis of XTE J2012+381 the PCA *Generic Event* timing mode data were used. We generated power density spectra (PDS) in the 0.001 – 4096 Hz frequency range using combined data of several consecutive observations in order to improve the statistical significance of the results. The resulting spectra were logarithmically rebinned to reduce scatter at high frequencies and normalized to the square root of fractional variability rms. The white noise due to the Poissonian statistics corrected for the dead-time effects, was subtracted (Vikhlinin, Churazov & Gilfanov 1994; Zhang et al. 1995; Revnivtsev, Gifanov & Churazov 2000).

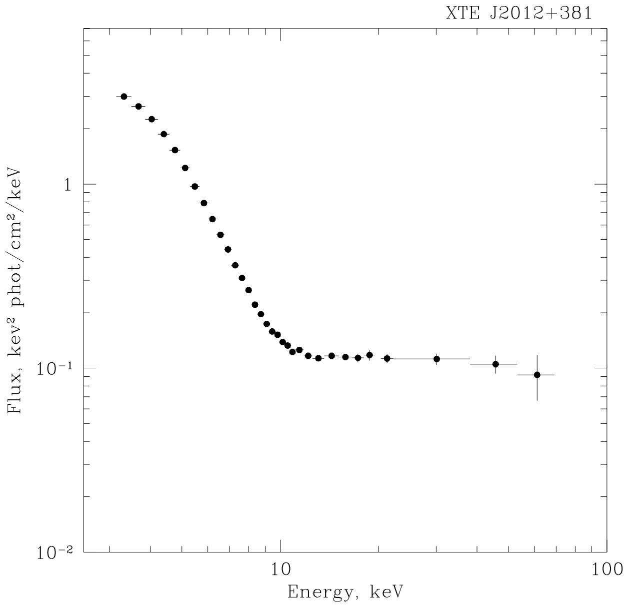

Fig. 3. Averaged broad band energy spectrum of XTE J2012+381 during observations #2 – #17 according to the data of PCA (3 – 20 keV) and HEXTE (20 – 80 keV) instruments.

3. Results

The X-ray flux history of the XTE J2012+381 outburst based on *RXTE*/PCA and ASM data in 1.3-12 keV energy range is shown in Fig.1 (presented ASM intensities provided by the RXTE/ASM team,

Table 2. Spectral parameters of XTE J2012+381, derived using a combination of a multicolor disc blackbody, power law and gaussian emission line. Parameter errors correspond to a 1σ confidence level for the assumed 1% systematic uncertainty of data.

#	$T_{\rm in}$, keV	$R_{\rm in}\cos i$ km[a]	α	Line Width keV	Eqw. Width eV	Flux[b]	χ^2 (dof)
1	0.79 ± 0.01	27.5 ± 1.4	2.2 ± 0.1	1.4 ± 0.1	825 ± 164	36.8 ± 1.1	35.1(33)
2	0.79 ± 0.01	38.7 ± 0.7	2.0 ± 0.0	1.1 ± 0.1	312 ± 32	49.6 ± 1.5	30.4(33)
3	0.80 ± 0.01	39.6 ± 0.8	2.0 ± 0.1	1.1 ± 0.1	297 ± 38	54.1 ± 1.6	38.8(33)
4	0.81 ± 0.01	39.5 ± 0.7	2.0 ± 0.0	1.2 ± 0.1	237 ± 32	56.9 ± 1.7	38.5(33)
5	0.81 ± 0.01	39.4 ± 0.7	2.0 ± 0.0	1.1 ± 0.1	178 ± 28	54.7 ± 1.6	35.8(33)
6	0.80 ± 0.01	40.1 ± 0.8	2.1 ± 0.1	1.0 ± 0.1	253 ± 42	55.0 ± 1.6	29.1(33)
7	0.80 ± 0.01	39.1 ± 0.8	2.0 ± 0.1	1.1 ± 0.1	302 ± 44	52.6 ± 1.6	24.9(33)
8	0.77 ± 0.01	41.3 ± 1.0	2.3 ± 0.1	0.8 ± 0.2	260 ± 70	49.3 ± 1.5	34.1(33)
9	0.76 ± 0.01	40.7 ± 0.8	2.7 ± 0.2	0.4 ± 0.1	133 ± 31	40.6 ± 1.2	30.1(33)
10	0.76 ± 0.01	40.0 ± 0.7	2.1 ± 0.1	1.0 ± 0.1	229 ± 34	38.2 ± 1.1	20.7(33)
11	0.75 ± 0.01	40.3 ± 0.7	2.7 ± 0.1	0.6 ± 0.1	153 ± 29	35.9 ± 1.1	29.0(33)
12	0.75 ± 0.01	39.2 ± 0.8	2.1 ± 0.2	1.0 ± 0.2	314 ± 69	34.4 ± 1.0	33.4(33)
13	0.73 ± 0.01	40.0 ± 0.7	2.3 ± 0.1	0.8 ± 0.1	259 ± 37	31.7 ± 1.0	40.9(33)
14	0.73 ± 0.01	39.1 ± 0.7	2.0 ± 0.1	1.1 ± 0.1	406 ± 44	31.0 ± 0.9	32.6(33)
15	0.72 ± 0.01	39.3 ± 0.8	2.1 ± 0.1	1.0 ± 0.1	363 ± 48	29.8 ± 0.9	31.9(33)
16	0.75 ± 0.01	38.3 ± 0.7	1.8 ± 0.1	1.4 ± 0.1	469 ± 67	32.7 ± 1.0	48.5(33)
17	0.76 ± 0.01	40.8 ± 0.7	2.8 ± 0.4	0.7 ± 0.2	165 ± 44	39.4 ± 1.2	28.2(33)
18	0.76 ± 0.01	38.6 ± 1.1	4.0 ± 0.5	0.6 ± 0.2	117 ± 45	37.6 ± 1.1	30.6(33)
19	0.76 ± 0.01	39.2 ± 0.7	3.1 ± 0.5	0.7 ± 0.2	192 ± 50	37.4 ± 1.1	23.7(33)
20	0.73 ± 0.01	40.7 ± 0.7	3.4 ± 0.4	0.5 ± 0.2	136 ± 44	31.8 ± 1.0	22.0(33)
21	0.72 ± 0.01	39.1 ± 0.7	2.0 ± 0.3	0.7 ± 0.2	285 ± 61	26.6 ± 0.8	28.8(33)
22	0.69 ± 0.01	40.0 ± 0.9	1.6 ± 0.4	1.1 ± 0.3	469 ± 160	21.9 ± 0.7	23.3(33)
23	0.68 ± 0.01	39.8 ± 0.7	3.1 ± 0.3	0.6 ± 0.1	248 ± 58	20.4 ± 0.6	26.2(33)
24	0.65 ± 0.01	35.3 ± 2.6	4.9 ± 0.4	0.0 ± 1.9	114 ± 51	16.8 ± 0.5	25.2(33)

[a] – assuming the source distance of 10 kpc
[b] – total X-ray flux in the $3-20$ keV energy range in units of $\times 10^{-10}$ erg s^{-1} cm^{-2}

http://xte.mit.edu/ASM_lc.html) . The evolution of the source flux in the soft X-ray band ($1.3-12$ keV as well as in the $3-20$ keV energy band) was characterized by the fast initial rise to a level of ~ 220 mCrab [1] on a time scale of $\sim$ a week followed by a $\sim$3 day long maximum and relatively slow decay, interrupted by secondary maximum $\sim$30 days after the beginning of the outburst. The subsequent outburst evolution was unusual because of long and powerful tertiary peak (close to 150 days from the beginning of the outburst).

The energy spectra of the X-ray transient were quite typical – a dominant soft thermal component with a rather weak power law tail.

Three PCA spectra (3-20 keV) are shown in Fig. 2. These spectra demonstrate once again that the soft spectral component in the spectra of X-ray Novae rise not instantly, but slightly after the power law component. Similar behavior was observed in Nova Muscae 1991 (Ebisawa et al. 1994), KS 1730-312 (Trudolyubov et al. 1996), GRS 1739-278 (Borozdin et al. 1998) and XTE J1748-288 (Revnivtsev, Trudolyubov & Borozdin 2000). The sequence of typical spectra is presented in Fig. 2. In Fig.2, one can see that during the first observation the

[1] Assuming a distance of 10 kpc the luminosity in the peak of the outburst is $\sim 7\times10^{37}$ erg s^{-1} in the $3-20$ keV energy band.

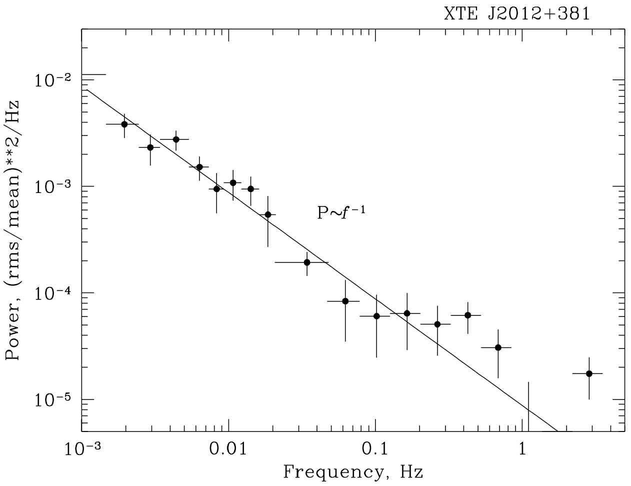

Fig. 4. Power spectrum of XTE J2012+381 averaged over observations #2 – #17 (PCA data, $3-20$ keV energy range).

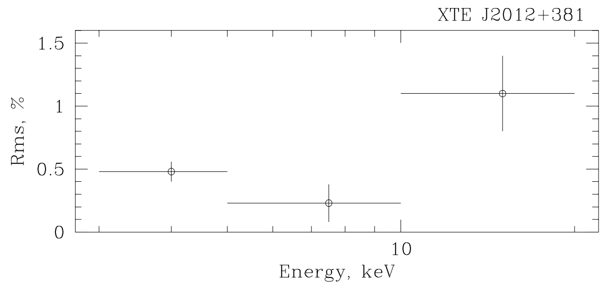

Fig. 5. The dependence of fractional rms variability of X-ray flux ($0.001 - 1$ Hz) of XTE J2012+381 on the photon energy.

soft component is not very strong (May 27, 1998), the second spectrum already has much more dominant soft component (June 1, 1998) and the third spectrum shows the weakening of the power law component (July 7, 1998).

A broad band spectrum from both the PCA and HEXTE, averaged over observations #2−#17 is presented in Fig.3. Low fluxes in gthe HEXTE limited our analysis to energies < 80 keV.

As it is clearly seen from Fig. 4, the average power density spectrum of the source is dominated by Very Low Frequency noise (VLFN) component, reasonably approximated by a simple power law model ($P \propto f^{\alpha}$) with a slope $\alpha = -1.08 \pm 0.06$ ($0.001 - 0.5$ Hz frequency range). We have not detected any statistically significant source flux variability at the frequencies higher than ~ 1 Hz. The $2\ \sigma$ upper limit on the possible Lorentzian component at $f \sim 500 - 1000$ Hz is approximately 2% for $Q = 10$ and 1% for $Q = 1$. In Fig. 5 the fractional rms amplitude of variability is shown as a function of the photon energy. In spite of a poor statistics (very low amplitude of X-ray variability), one can see that there is an indication on the rise of the rms with energy. Such dependence is quite typical for the emission of black hole candidates in the Very High State (VHS)(see discussion of such behavior in Churazov, Gilfanov & Revnivtsev 2000).

4. Discussion

The the properties of the outburst of XTE J2012+381 are very similar to those of the X-ray Novae that have been associated with black hole candidates. It has a FRED (fast-rise-exponential-decay) light curve, with secondary maxima, as is typical for X-ray transients (Chen, Shrader & Livio 1997).

The spectrum of the source can be well described by standard two-component model which is typical for black hole candidate X-ray binaries (Tanaka & Lewin 1995). The evolution of the energy spectrum of XTE J2012+381 can be characterized as a gradual increase of the contribution of the soft thermal component as the overall X-ray flux decreases.

Our calculations show that the value of model parameter $R_{in} \cos i$, inferred from the soft spectral component approximation is nearly constant during the decay phase of the outburst (Table 2) in general agreement with earlier results of Zhang et al. 1998. However we believe that it is premature to assume a constant radius of inner accretion disk during the outburst. [2]

The PDS of XTE J2012+381 is also very typical for the VHS of black hole candidates with dominant soft spectral component. The energy dependence of the fractional rms provided another hint at the universal correlation between the amplitude of the variability and relative strength of the hard spectral component.

Acknowledgements. This research has made use of data obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA/Goddard Space Flight Center.

References

Borozdin K. N., Revnivtsev M. G., Trudolyubov S. P., Aleksandrovich N. L., Sunyaev R. A., Skinner G. K., 1998, Astr.L. 24, 435

Bradt, H., Swank, J., & Rothschild, R. 1993, A&AS, 97, 355

Chen W., Shrader C. R., Livio M., 1997, ApJ, 491, 312

Churazov E., Gilfanov M., Revnivtsev M. 2000, MNRAS, submitted, astro-ph/0006227

Ebisawa K., Ogawa M., Aoki T., Dotani T., Takizawa M., Tanaka Y., Yoshida K., Miyamoto S., Iga S., Hayashida K., Kitamoto S., Terada K., 1994, PASJ, 46, 375

Hjellming, R. M., Rupen, M. P., Mioduszewski, A. J. 1998, IAU Circ. 6924

Hynes, R. I., & Roche, P. 1998, IAU Circ. 6932

Leahy, D. A. et al. 1983, ApJ, 266, 160

Marshall, F. E., & Strohmayer, T. 1998, IAU Circ. 6922

Mitsuda K., Inoue H., Koyama K., Makishima K., Matsuoka M., Ogawara Y., Suzuki K., Tanaka Y., Shibazaki N., Hirano T., 1984, PASJ, 36, 741

Pooley G.G. 1998, IAUC 6926

Remillard, R., Levine, A., & Wood, A. 1998, IAU Circ. 6920

Revnivtsev M., Gilfanov M., Churazov E. 2000, submitted to A&A, astro-ph/0007092

Revnivtsev M., Trudolyubov S., Borozdin K. 2000, MNRAS 315, 665

Shakura, N.I., & Sunyaev, R.A. 1973, A&A, 24, 337

Shimura, T., & Takahara, F. 1995, ApJ, 445, 780

Tanaka Y., Lewin W. H. G., 1995, in X-ray Binaries, ed. W. Lewin, J. van Paradijs, E. van der Heuvel (Cambridge: Cambridge Univ. Press), 126

Trudolyubov, S.P., Gilfanov, M.R., Churazov, E.M., Borozdin, K.N., Aleksandrovich, N.L., Sunyaev, R.A., Khavenson, N.G., Novikov, B.S., Vargas, M., Goldwurm, A., Paul, J., Denis, M., Borrel, V., Bouchet, L., Jourdain, E., Roques, J.-P. 1996, Astron. Lett., 22, 664

[2] Note that no corrections to the electron scattering and general relativity were made in the soft spectral component model (Shakura & Sunyaev 1973, Shimura & Takahara 1995). This model assumes incorrect radial dependence of the disk effective temperature within ~ 5 gravitational radii. Thus the inferred value of the effective radius R_{in} should not be treated as the actual size of the optically thick emitting region.

Vikhlinin A., Churazov E., Gilfanov M., 1994, A&A, 287, 73
White N.E., Ueda Y., Dotani T. et al. 1998, IAUC 6927
Zhang W., Jahoda K., Swank J., Morgan E., Giles A., 1995, ApJ, 449, 930
Zhang, S. N., Sun, X., Cui, W., Chen, W., Swank, J. 1998, AAS Meeting 193, 93.05