A&A 424, L5–L8 (2004)
DOI: 10.1051/0004-6361:200400012

Astronomy & Astrophysics

Letter to the Editor

First simultanous X-ray and optical observations of rapid variability of supercritical accretor SS433

M. Revnivtsev[1,2], R. Burenin[2], S. Fabrika[3], K. Postnov[4], I. Bikmaev[5], M. Pavlinsky[2], R. Sunyaev[1,2], I. Khamitov[6], and Z. Aslan[6,7]

[1] Max-Planck-Institute für Astrophysik, Karl-Schwarzschild-Str. 1, 85740 Garching bei München, Germany
e-mail: mikej@mpa-garching.mpg.de
[2] Space Research Institute, Russian Academy of Sciences, Profsoyuznaya 84/32, 117810 Moscow, Russia
[3] Special Astrophysical Observatory, Nizhnij Arkhyz, Karachaevo-Cherkesiya, 369167, Russia
[4] Sternberg Astronomical Institute, 119992, Moscow, Russia
[5] Kazan State University, Kremlevskaya str.18, 420008, Kazan, Russia
[6] TUBITAK National Observatory, Akdeniz Universitesi Yerleskesi, 07058, Antalya, Turkey
[7] Akdeniz University, Physics Dept. 07058, Antalya, Turkey

Received 21 May 2004 / Accepted 24 June 2004

Abstract. We present results of first simultaneous optical and X-ray observations of peculiar binary system SS433. For the first time, chaotic variability of SS433 in the optical spectral band (*R* band) on time scales as small as tens of seconds was detected. We find that the X-ray flux of SS433 is delayed with respect to the optical emission by approximately 80 s. Such a delay can be interpreted as the travel time of mass accretion rate perturbations from the jet base to the observed X-ray emitting region. In this model, the length of the supercritical accretion disk funnel in SS433 is $\sim 10^{12}$ cm.

Key words. accretion, accretion disks – black hole physics – instabilities – stars: binaries:general – X-rays: general – X-rays: stars

1. Introduction

SS433 is the unique X-ray binary, demonstrating precessing jets and supercritical accretion disk around a black hole (Margon 1984; see Fabrika 2004 for a recent review). The total luminosity of the system is estimated to be at a level of 10^{40} erg/s, with most of this luminosity coming in UV and optical bands (Cherepashchuk et al. 1982; Dolan et al. 1997). According to the current model of this binary, the dense outflowing wind and the geometrically thick accretion disk totally cover from us the direct X-ray emission from the innermost hot regions of the accretion disk. The early observations of SS433 by EXOSAT and *ASCA* satellites led to the conclusion that standard X-ray emission in SS433 originates in optically thin plasma outflowing in a mildly relativistic, $v = 0.26c$, jets (Watson et al. 1986; Kotani et al. 1996). A detailed analysis of high-resolution *Chandra* observations of SS433 suggests that the X-ray jet consists of well collimated freely expanding cooling plasma with temperature varying from 20 to 0.5 keV. The size of the vizible X-ray jet is estimated to be $\sim 10^{10}-10^{11}$ cm (Marshall et al. 2002). This is the lower limit on the size of X-ray emitting jet if heating effects are not important (Brinkmann & Kawai 2000). The observed X-ray luminosity ($\approx 10^{36}$ erg/s) is only a tiny part of the total jet power. For example, the kinetic power of the jet is estimated to be 1000 times larger than the observed X-ray luminosity. The contribution of the observed X-ray luminosity to the total energetics of the system is even smaller – not more than 10^{-4}.

The long-term behavior of SS433 has been well studied at different wavelengths. The source demonstrates different types of long-term periodicities: precessional (162.3 days), orbital (13.082 days), and nutational (6.28 days) ones. SS433 exhibits noticeable variability on shorter times as well, however at time scales smaller than hours this has been poorly studied. For example, erratic variability with an amplitude of $5-10\%$ on a time-scale of a few minutes was found in the optical band by Goranskii et al. (1987) and Zwitter et al. (1991). Recently, Kotani et al. (2002) detected X-ray variability of SS433 (RXTE, PCA) on a time scale of ~ 50 s, when the source was in its active state.

The accretion disk can modulate energy release and luminosity in the broad range of time scales (Lyubarskii 1997). This mechanism can nicely explain the observed flicker-noise spectra found in some X-ray binaries, e.g. Cyg X-1 (Churazov et al. 2001). In the case of SS433 the X-ray emission of the accretion disk is not directly visible, so variability in the optical and UV may be a better indicator of the temporal properties of the accretion disk.

The UV and optical radiation of SS433 is well approximated by a single reddened black body source (Cherepashchuk et al. 1982; Dolan et al. 1997; Gies et al. 2002) with a temperature $T_e \sim 5\times10^4$ K ($A_V \approx 8$) and a size $r_{ph} \sim (1-2)\times10^{12}$ cm. The bulk of the optical and UV emission most likely escapes from the hot funnel in the photosphere close to the jet bases (Dolan et al. 1997; Fabrika 2004). Should X-ray and optical variabilities be due to one physical reason (e.g., the accretion rate modulation), simultaneous observations of SS433 in the optical band (which reflect variability of the energy release in the supercritical accretion disk) and in X-rays (that come from the footpoint of the jet) will be invaluable to test the origin of jets in SS433 and their close surroundings.

In this paper we present the analysis of simultaneous optical and X-ray observations of SS433 in March 2004.

2. Observations and data analysis

2.1. RTT150

Optical observations of SS433 were performed with 1.5-m Russian-Turkish Telescope (RTT150) at TÜBITAK National Observatory (TUG), Bakyrly mountain, 2547 m, Turkey, $2^h01^m20^s$ E, 36°49′30″ N. The object was observed as a target of opportunity, in order to support INTEGRAL and RXTE observations in optical.

Observations were performed on March 25 (0:33−3:08 UT) and March 27 (0:18−3:20 UT) under clear sky and poor seeing (≈2″) conditions. We used low readout noise back-illuminated 2 × 2 K Andor Technologies DW436 CCD, mounted in F/7.7 Cassegrain focus of the telescope. In our observations we used R filter because the Galactic absorption in R is significantly lower than in blue bands and SS433 is quite bright in R ($R \approx 12$).

To improve the temporal resolution of our measurements we used only a small CCD subframe which contains small part of the field near the object. Also we used 4 × 4 binning mode and high readout speed mode of the CCD. Time resolution ≈3.4 s with 1 s exposure was obtained. The data reduction was done with IRAF (Image Reduction and Analysis Facility)[1] and using our own software. Bias and dark counts were subtracted and flat field correction applied for all the images. Apart of SS433 our subframe contains few bright stars which were used as reference for differential photometry. All stars were centered only once, using one reference image. Centers of stars in other images were calculated from their shifts, therefore centering errors (if any) are exactly the same in object and reference stars.

2.2. RXTE

X-ray observations of SS433 were performed by the RXTE observatory (Bradt et al. 1993) on March 25 and 27 in respond to the TOO request. The total exposure time of two observations amounts to about 4 ks. In order to study the variability of the source we used primarily the Proportional Counter Array (PCA) data, which have large effective area. Data reduction of the RXTE/PCA data was done using standard tasks of the LHEASOFT/FTOOLS 5.2 package. In order to improve the statistics of the lightcurve, we used data from all operational detectors but PCU0, which lacks propan veto layer. As the source is relatively weak, for the background modelling we accepted CMl7_240 model.

[1] http://tucana.tuc.noao.edu/

3. Results

During our observations, SS433 was observed in the orbital elongation (March 25) and the superiour conjunction of the accretion disk (March 27), while the precessional phase was close to the most open disk. Both binary and precessional phases are most favourable for studying the base of the blue jet. Radio monitoring of SS433 indicated (Trushkin 2004) that in the beginning of March, 2004, the source entered into its active state with several strong flares on March 10−16, 2004.

Two sets of simultanous optical and X-ray measurements of the flux of SS433 by RTT150 and RXTE were obtained. The observed lightcurves are presented in Fig. 1. During both observations chaotic variability is clearly visible in both optical and X-ray lightcurves. The power spectrum of this variability can be described by a simple power law from frequencies where the statistical noise dominates (∼0.05−0.1 Hz) down to 10^{-4} Hz. The slope of the power law in the optical band (R filter) is $\alpha = -1.7\pm0.1$ (see Fig. 2). The same power law can also describe the power spectrum obtained from X-ray data. In the frequency band 5×10^{-4}–0.01 Hz, the amplitude of variability is approximatety 1.5 ± 0.2% and 6.5 ± 1.4% for optical and X-ray lightcurves, respectively.

The statistically significant chaotic source variability in both optical and X-ray band allow us to study their crosscorrelation. It is a big advantage for us that the lightcurves of SS433 do not demonstrate detectable quasiperiodical variability, because in this case interpretation of the crosscorrelation picture would be ambiguous.

The relatively high fractional stochastic variability of the optical and X-ray flux enabled us to carefully check the stability of the crosscorrelation pattern. To this end, we split all overlaping lightcurves into 256-s intervals and inside each interval calculated X-ray-to-optical crosscorrelation. Then we averaged the obtained crosscorrelations and calculated the root mean square deviations of crosscorrelations in individual intervals from the average one. The resulted average crosscorrelation is presented in Fig. 3. The dashed region shows the rms deviations of individual crosscorrelations from the average one. One can clearly see from the plot that the X-ray lightcurve lags the optical one (negative time lag means that the optical variability preceeds the X-ray one).

4. Discussion

Simultaneous observations of SS433 in optical and X-ray energy bands demonstrate clear correlation of measured fluxes. The variable part of the X-ray lightcurve is delayed with respect to the optical one by about 80 s.

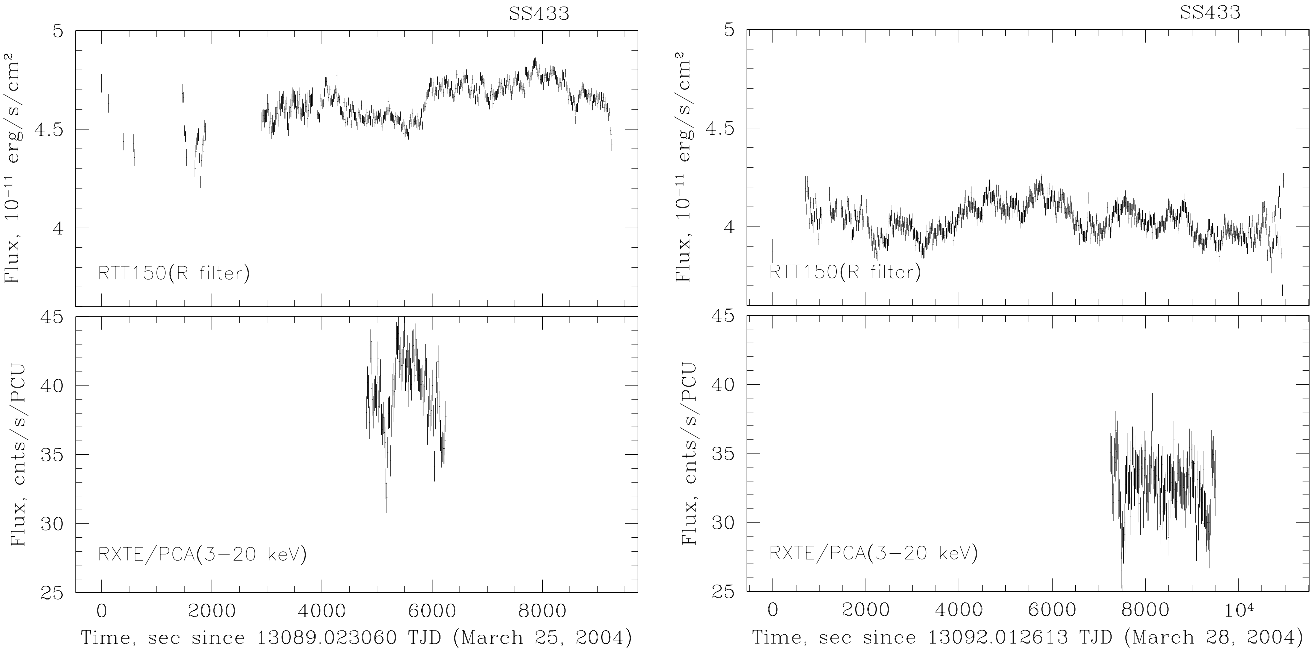

Fig. 1. Lightcurves of SS433 in the optical (RTT150, *R*-band) and X-ray (RXTE/PCA, 3−20 keV) energy bands.

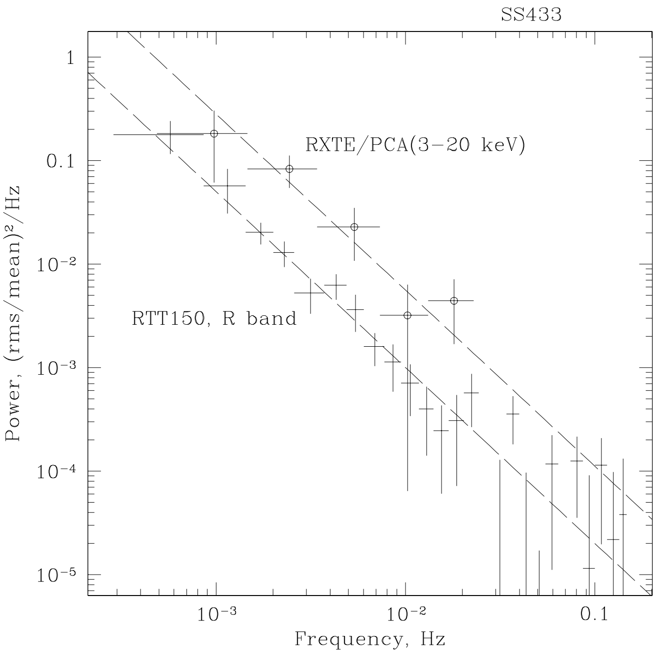

Fig. 2. Power spectra of the optical and X-ray lightcurves of SS433. The dashed line is the best fit model to the optical power spectrum. For X-ray points this power law was rescaled.

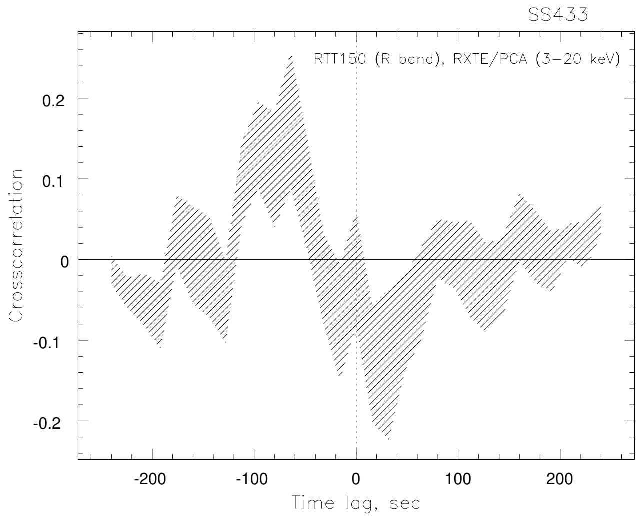

Fig. 3. Crosscorrelation of X-ray and optical lightcurves of SS433.

The lag of X-rays with respect to the optical variability can be anticipated in the framework of the cooling jet model that appears as a result of acceleration of matter in the base of the funnel in the center of the supercritically accretion disk (Calvani & Nobili 1981; Bodo et al. 1985; Eggum et al. 1988; Okuda 2002).

The variability of SS433 on longer time scales with lagged correlation has been known in different parts of the emitting regions of this system (Cherepaschuk 2002; Fabrika 2004). For example, the optical nutation variability has been observed to preceed the nutation motion of optical jets by 0.6 days. This is exactly the time it takes for the jet gas to travel from the compact object to the Hα emitting region downstream the jets. A maximum of Hα emission in the optical jets forms at a distance of 4×10^{14} cm from the source (Borisov & Fabrika 1987). The amplitude of the nutation variability (Cherepaschuk 2002) is $\Delta V \approx 0.17$ and increases in shorter *B* band. This nutational lag proves that the optical and UV radiation come from the inner wind region, i.e. from the jet base, but not from the jet itself. The jets' energy budget ($L_{\rm kin} \sim 10^{39}$ erg/s, $L_{\rm x} \sim 10^{36}$ erg/s) is insufficient to provide the optical nutational modulation, which is 20% of $L_{\rm opt} \sim 10^{38}$ erg/s, $L_{\rm UV} \sim 10^{40}$ erg/s.

In our case we are dealing with two nearby emitting regions – the innermost region of the supercritical accretion disk, which emits most of the energy in the optical and UV band, and the X-ray emitting jet, which is supposed to be launched near the compact object and have a bulk velocity of $0.26c$. The most straightforward and simplest interpretation of the observed time delay between the optical and X-ray fluxes, which does not contradict the common knowledge about SS433, can be as follows.

Mass accretion fluctuations appear in the bottom of the supercritical disk funnel where the jet is being formed and results in fluctuating X-ray flux inside the funnel. According to the supercritical disk simulations (Eggum et al. 1988; Okuda 2002), the place of the jet formation ($10{-}100\ r_{\rm g}$) is quite close to the black hole. The X-ray radiation coming upwards the funnel may be absorbed by the outer funnel walls (which are directly observed or lie immediately close to the directly observed parts of the funnel) and produce fluctuating UV-optical radiation via photoabsorption. Similar processes are well-known to operate in low mass X-ray binaries (see e.g. Lawrence et al. 1983). In this case the variable X-ray emission might contain the imprint of the reprocessing mechanism and geometry of the reprocessing region. The amplitude of the reprocessed X-ray emission can not be larger than ~5% (the total amplitude of the X-ray variability). We plan to study the variable part of X-ray emission of SS433 in more detail later.

The same fluctuations reach the observed part of the X-ray jet after the jet propagation time inside the funnel and may appear as variable fraction of the visible X-ray emission. This is the basic mechanism we propose to explain the correlated X-ray – optical variability. It is important that this correlated variability between optical and X-ray variations has to be related to all time-scales generated in the accretion disk, because we do not see a QPO-like variability.

The delayed X-ray variability allows us to estimate the funnel length $r_{\rm f}$ in SS433. The time it takes for the X-ray jet to appear above the funnel edge is $r_{\rm f}/V_{\rm j}$, the time for the light to reproduce optical emission via photoabsorption of X-rays from the funnel bottom is $\eta r_{\rm f}/c$, where factor $\eta \gtrsim 1$ is responsible for possible delays (geometry, scattering, etc.). The difference between these two times yields the time delay between the optical and X-ray variabilities found by us, $\Delta t \sim 80$ s. So for the funnel length we have the estimate $r_{\rm f} \sim 2\times 10^{12}/(c/V_{\rm j}-\eta)$ cm. A lower limit on the funnel length is for $\eta = 1$, i.e. $r_{\rm f} \gtrsim 10^{12}$ cm. So the bases of the X-ray jets, whose length $\gtrsim 10^{10}{-}10^{11}$ cm were derived from the *Chandra* spectra (Marshall et al. 2002), have to be placed at distance $r_{\rm f} \sim 10^{12}$ cm from the black hole.

Acknowledgements. The authors thank S. A. Trushkin for drawing their attention to the activity of SS433 in March 2004, to A. I. Zakharov for helpful discussions. The authors are grateful to the RXTE planning team for rapid responce to the TOO request. This work was partially supported by grants of Minpromnauka NSH-2083.2003.2, NSH-1789.2003.02 and program of Russian Academy of Sciences "Non-stationary phenomena in astronomy". Partial support through RFBR grants 03-02-16110, 04-02-16349 and 02-02-17174 is acknowledged. MR, RB, IB and MP thank International Space Science Institute (ISSI, Bern) for partial support. Research has made use of data obtained from High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA/Goddard Space Flight Center.

References

Bodo, G., Ferrari, A., Massaglia, S., & Tsinganos, K. 1985, A&A, 149, 246
Borisov, N. V., & Fabrika, S. N. 1987, SvA Lett. Astron., 13, 200
Bradt, H., Rotshild, R., & Swank, J. 1993, A&AS, 97, 355
Brinkmann, W., & Kawai, N. 2000, A&A, 363, 640
Calvani, M., & Nobili, L. 1981, Ap&SS, 79, 387
Cherepaschuk, A. 2002, Space Sci. Rev., 102, 23
Cherepashchuk, A. M., Aslanov, A. A., & Kornilov, V. G. 1982, SvA, 26, 697
Churazov, E., Gilfanov, M., & Revnivtsev, M. 2001, MNRAS, 321, 759
Dolan, J. F., Boyd, P. T., Fabrika, S., et al. 1997, A&A, 327, 648
Eggum, G. E., Coroniti, F. V., & Katz, J. I. 1988, ApJ, 330, 142
Fabrika, S. 2004, Astrophys. Space Phys. Rev., 12, 1
Gies, D. R., McSwain, M. V., Riddle, R. L., et al. 2002, ApJ, 566, 1069
Goranskij, V. P., Kopylov, I. M., Rakhimov, V. Yu., et al. 1987, Commun. Spec. Astrophys. Obs., 52, 5
Kotani, T., Kawai, N., Matsuoka, M., & Brinkmann, W. 1996, PASJ, 48, 619
Kotani, T., Trushkin, S., & Denissyuk, E. K. 2002, in New Views on Microquasars, the Fourth Microquasars Workshop, ed. Ph. Durouchoux, Y. Fuchs, & J. Rodriguez, Center for Space Physics, Kolkata, India, 257
Lawrence, A., Cominsky, L., Engelke, C., et al. 1983, ApJ, 271, 793
Lyubarskii, Yu. 1997, MNRAS, 292, 679
Margon, B. 1984, ARA&A, 22, 507
Marshall, H. L., Canizares, C. R., & Schulz, N. S. 2002, ApJ, 564, 941
Okuda, T. 2002, PASJ, 54, 253
Trushkin, S. A. 2004, `http://cats.sao.ru/ satr/XB/SS433/`
Watson, M., Stewart, G., Brinkmann, W., & King, A. 1986, MNRAS, 222, 261
Zwitter, T., Calvani, M., & D'Odorico, S. 1991, A&A, 251, 92