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Letter to the Editor

INTEGRAL observations of SS433, a supercritically accreting microquasar with hard spectrum★

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Abstract. Observations of SS433 by INTEGRAL carried out in March–May 2003 are presented. SS433 is evidently detected on the INTEGRAL images of the corresponding sky region in the energy bands 25–50 and 50–100 keV. The precessional variability of the hard X-ray flux is clearly seen. The X-ray eclipse caused by the binary orbital motion is also detected. A possible origin of the hard continuum is briefly discussed.

Key words. X-ray: binaries – observations

1. Introduction

SS433 is a unique galactic X-ray binary system – a microquasar with mildly relativistic ($v = 0.26c$), narrow-collimated (opening angle $\theta \sim 1^\circ$, Namiki et al. 2003), precessing jets (Margon 1984; Cherepashchuk 1981, 1988; Crampton & Hutchings 1981). The system exhibits three photometric and spectral periodicities related to precession ($P_{\rm prec} = 162\overset{\rm d}{.}5$), orbital ($P_{\rm orb} = 13\overset{\rm d}{.}082$) and nutation ($P_{\rm nut} = 6\overset{\rm d}{.}28$) periods (Goranskii et al. 1998). Recent spectral observations (Gies et al. 2002a) revealed the presence of absorption lines in the spectrum of the optical A (~A7Ib) supergiant companion. The observed orbital Doppler shifts of the optical star absorption lines correspond to the mass ratio of relativistic ($m_{\rm x}$) and optical ($m_{\rm v}$) component $q = m_{\rm x}/m_{\rm v} = 0.57 \pm 0.11$ and masses $m_{\rm v} = (19 \pm 7)\,M_\odot$, $m_{\rm x} = (11 \pm 5)\,M_\odot$. Similar characteristics were derived from optical light curves of SS433 (Antokhina & Cherepashchuk 1987).

Recent infrared spectroscopy (Fuchs et al. 2002) indicated an enhanced helium abundance in the matter outflowing from the optical star into the superaccreting precessing accretion disc. This confirmed the evolutionary status of SS433 as a massive X-ray binary at an advanced evolutionary stage (Cherepashchuk 1981, 1988) with supercritical accretion (Shakura & Sunyaev 1973). The new spectroscopic data (Gies et al. 2002a) may indicate that the observed large width of X-ray eclipse in SS433 can be due to collision stellar winds of the binary components (Cherepashchuk et al. 1995). So it is established now that SS433 is a microquasar with a black hole (BH), supercritical precessing accretion disc and precessing quasi-stationary relativistic jets.

It is well known that X-ray spectra of BH X-ray binaries, in contrast to accreting neutron stars, show power-law tails extending up to many hundreds keV (Sunyaev et al. 1991a,b). In supercritical accretion regime the thermalisation of X-ray emission within the optically thick wind outflowing from the supercritical accretion disk is expected to cut off the spectrum of an accreting BH at comparatively low energies, of order of tens keV. At the same time, geometrical factors, such as the tunnel swept by the relativistic jets in the disc wind, leave the hope to observe the possible hard X-ray component from SS433 at least in the precession phases when the disk is observed mostly face-on (under the inclination angle ~30°).

In this paper we report on the searches for hard X-ray component from the supercritically accreting BH in SS433 using the dedicated INTEGRAL observations carried out in May 2003. We also use the INTEGRAL data on SS433 obtained during observations of Aql X-1 (Molkov et al. 2003) in March 2003.

Hard X-ray emission of SS433 had been observed before by RXTE (Kotani et al. 2002). The IBIS detector onboard the INTEGRAL satellite offers a unique possibility of studying SS433 in hard X-rays up to hundreds keV (for more detail on INTEGRAL scientific payload and mission description see Winkler 1996, 1999).

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2. Observations and data reduction

The international gamma-ray observatory INTEGRAL was successively launched to its orbit with a Russian rocket PROTON from the Baikonur cosmodrome on Oct. 17, 2002. The scientific payload includes instruments designed for the investigation of cosmic sources in a wide energy band 3–10 000 keV: 1) the IBIS telescope, consisting of the two detectors ISGRI and PICsIT working in the energy band 15–10 000 keV, and allowing sources localization with an accuracy of about 30′′; 2) the spectrometer SPI, which works in an energy band 15–8000 keV and is designed for an accurate spectroscopy with the energy resolution $E/\delta E \simeq 500$ (at 1 MeV); 3) the X-ray monitor JEM-X with an effective energy range 3–35 keV. All telescopes are using the principle of coding aperture. The full field of view (FOV) of IBIS telescope, data from which is used in this work is $25^\circ \times 25^\circ$ with fully coded FOV $9^\circ \times 9$ (FCFOV).

SS433 has been observed by INTEGRAL in two sets on 11, 23, 30 March, 6, 13 April and May 3–9 and 11, 2003, with a total duration of about 500 ks. At this time, SS433 was seen maximally face-on which favored observations of the deepest parts of the "tunnel" worked out by the jets in the disk wind. On May 3, the accretion disk was nearly in front of the optical star and on May 11 it was partially shielded by the optical companion. So these observations allowed us to detect both the total X-ray emission from the jets and the X-ray emission from jets with subtracted central parts shielded by the optical star. Consequently, we can study the "pure" spectrum of the very central jet parts close to the BH. Here we present a preliminary quick-look analysis of May 3–8 observations when the optical star was located behind the accretion disc. These observations relate to the total emission of the X-ray jet, including its central part.

In addition, we have used the INTEGRAL data on SS433 obtained during observations of Aql X-1 (Molkov et al. 2003) in March–April 2003 to study its hard X-ray long-term variability, motivated by the precessional motion observed in SS433.

Calibrations of instruments of INTEGRAL observatory is still not finished, and right now it is not possible for us to make full analysis of data of all telescopes. Therefore, our paper focuses on the data from the IBIS telescope which has the largest effective area.

For data reduction, we used the standard software package OSA 1.0, distributed by INTEGRAL Science Data Center (ISDC, `http://isdc.unige.ch`). This version does not allow us to make a full spectral and timing analysis of data, therefore for the preliminary spectral analysis of SS433 we used a big set of public calibration observations of the Crab nebula obtained in February 2003 (revolutions 39–45). Taking into account the present uncertainties of the calibrations leading to strong dependence of the reconstructed source intensity on its distance from the center of FOV (obtained from the Crab nebula analysis), especially in low channels of the ISGRI detector, in our subsequent analysis we used only the data of observations when SS433 was inside FCFOV, where the intensity of the source should be relatively stable. The count rates for the the Crab nebula which were used for the calibration are 131 counts/s and 89 counts/s in 25–50 and 50–100 keV energy bands, respectively.

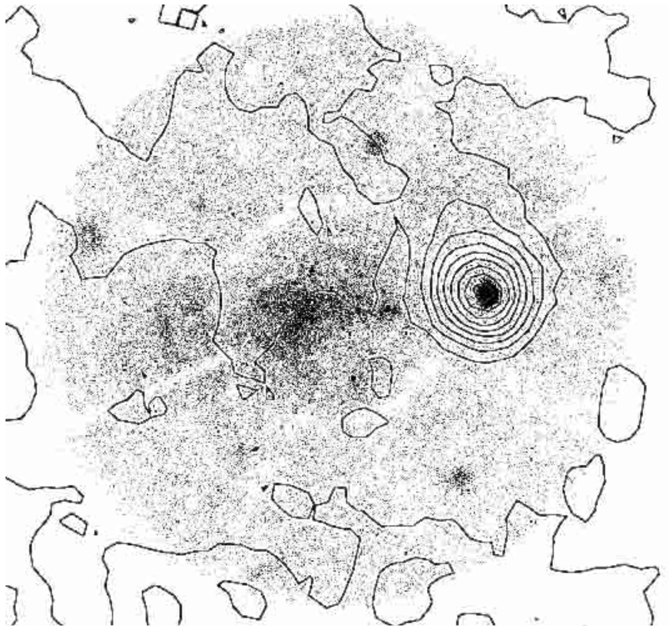

Fig. 1. Comparison of the ROSAT and IBIS images of SS433. Nothing except the central source is detected by IBIS (isolines are IBIS counts per pixel.)

A reconstruction of the sky regions was made using May 2003 data with the total exposures of ISGRI detector ∼450 ks (orbits 67, 68, 69, 70) for the image reconstruction and ∼200 ks (orbits 67, 68) for spectral analysis.

3. Results

3.1. Position accuracy of IBIS and the SS433 image shape

The accuracy of object positions obtained by IBIS has been tested using the four identified sources – SS433, Aql X-1, Ser X-1 and GRS 1915+105. The result is that there is a systematic shift in the sources' position determination of ∼3.9′ with dispersion ∼2′ The systematic shift is mostly along the RA coordinate. So the X-ray source coincides with the optical position of SS433 within the 2′ error. The position accuracy can be ameliorated in future calibrations.

On the IBIS images, SS433 appears point-like with a radius of ∼4′, without any significant deviation of isophots from the circular form. Any extended details such as jets or lobes are not detected. For comparison, in Fig. 1 we plot the ROSAT image of SS433 superimposed on the IBIS 25–50 contours (in counts per pixel). The extended X-ray lobes seen on the ROSAT image are not detected on the IBIS/ISGRI images by the existing software possibly due to insufficient sensitivity and uncertainties in the background subtraction, "hot" pixels tackling procedure, etc.

SS433 is distinctly seen in the IBIS FOV at 25–50 keV (Fig. 2) and 50–100 keV (3) energy band, along with the famous microquasar GRS1915+105 hosting a sub-critically accreting BH. The very fact of the good seeing of SS433 up to

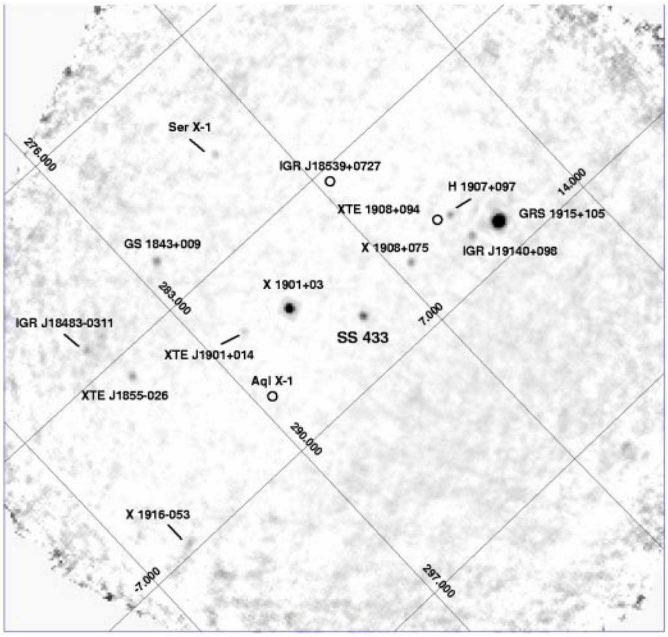

Fig. 2. Map of the sky around SS433 (in counts per second per pixel) obtained by IBIS/ISGRI telescopes on May 2003 in 25–50 keV energy band. The coordinate grid is plotted in the J2000 equatorial system.

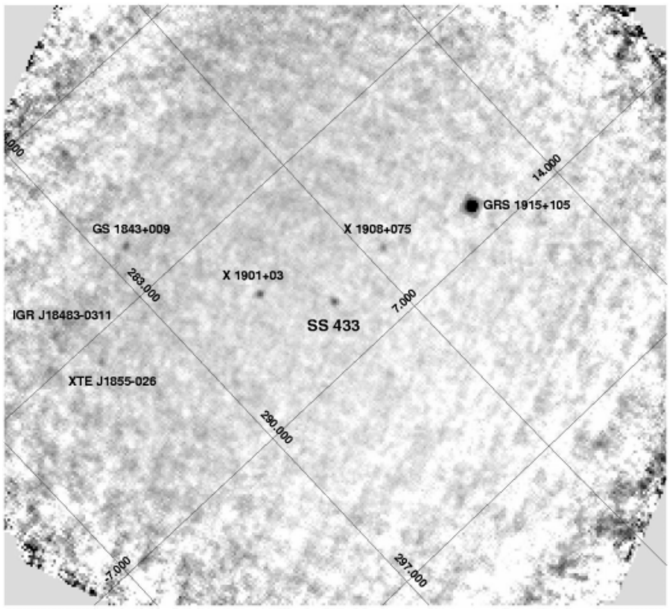

Fig. 3. Map of the sky around SS433 (in counts per second per pixel) obtained by IBIS/ISGRI telescopes on May 2003 in 50–100 keV energy band. The coordinate grid is plotted in the J2000 equatorial system.

100 keV evidences for important role of the geometrical factor (precessing accretion disk) and may suggest the presence of relativistic particles in the vicinity of the supercritically accreting BH (see below).

3.2. The hard X-ray luminosity of SS433

SS433 is known to be a moderately bright X-ray source in the 2–10 keV energy band with $L_x \sim 10^{35}$–10^{36} erg/s (Marshall et al. 2002; Namiki et al. 2003) which is mainly due to jet emission. The luminosity of SS433 in the hard X-rays as inferred from the May 3 INTEGRAL observations is $L_x \sim 3\times10^{35}$ erg/s (25–50 keV) and $L_x \sim 1.2\times10^{35}$ erg/s (50–100 keV), assuming the distance of 4.85 kpc (Vermeulen et al. 1993) Thus, the total X-ray luminosity of SS433 is less than that of classical high-mass X-ray binaries with OB-supergiants (e.g., Cherepashchuk et al. 1996).

3.3. Hard X-ray variability of SS433

The X-ray flux (2–10 keV) from SS433 is observed by RXTE to be variable on timescales 100–1000 s (Kotani et al. 2002). This timescale corresponds to Keplerian frequencies at distances from 10 $M_\odot$ BH where the 1000 km s^{-1} disk wind is formed. Hard X-rays from the jet could also have such a variability, so we tried to analyze our data to find it. The hard X-ray variability formed at the very basement of the jets provides information on the jet production and collimation. We found evidence neither for periodic pulsations on timescales 400–4000 s, nor quasiperiodic oscillations (typical for subcritically accreting BH).

The light curves of SS433 from the IBIS/ISGRI detector exhibit precessional and orbital variability in the 25–50 keV band. The variations of the flux from 7 to 25 mCrab are clearly detected in the pointings of March 11, 23, 30 and April 6, 13 as well as on May 3–9, 11. The precessional variability is traced from the cross-over phase (on March 8), when the disk is seen edge-on and the X-ray flux is minimal, up to the maximum phase (on May 1), when the disk is maximally open to the observer. The flux changes more than two times in magnitude with the precession phase in the 25–50 keV band (see Fig. 4). The amplitude of the precessional variability in the 2–12 keV band as inferred from RXTE ASM data (Gies et al. 2002b) is smaller, ~40%.

The pointings of May 9 and 13, 2003 show the decrease of the flux from 25 down to 7 mCrab, which is apparently due to an X-ray eclipse in the primary orbital minimum when the "normal" star is in front of the compact source (on May 11). The eclipse phase agrees with the ephemeris given by Goranskii et al. (1998) calculated using optical data only. The X-ray eclipse egress is clearly seen as a sharp flux increase. Though the observation sequence is not continuous, the X-ray eclipse duration is estimated to be ≈2 days. Note that the X-ray flux exhibits essential decrease in all the observed moments of the expected optical eclipses (shown as black triangles in Fig. 4), most clearly on April 2 and May 11. The eclipses in the 25–50 keV band are deep and sharp, which possibly indicates that the eclipsed emission originates from the compact source itself or from the inner parts of the jets.

3.4. Hard X-ray spectrum of SS433

Despite the preliminary character of our analysis, the hard X-ray spectrum of SS433 appears relatively flat from 20 keV to 100 keV (Fig. 5) with the power-law photon index $\alpha \sim -2$.

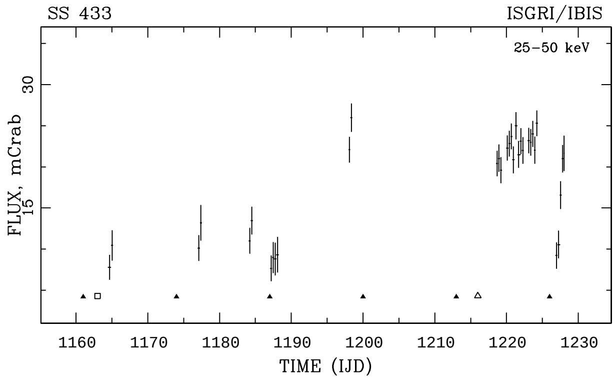

Fig. 4. Light curve of SS433 (IBIS/ISGRI telescope, 25–50 keV) on March–May 2003. IJD (INTEGRAL Julian Date) = MJD – 51544. The filled triangles indicate optical eclipse minima according to Goranskii et al. (1998). The white triangle and square indicate the precessional phases of face-on and cross-over respectively.

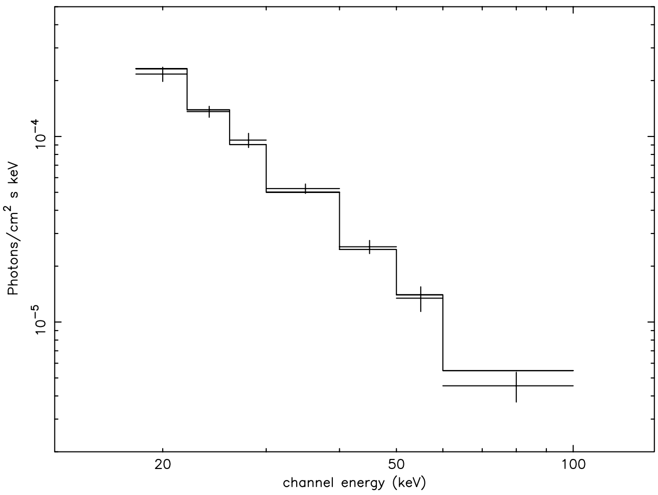

Fig. 5. The spectrum of SS433 (IBIS telescope, ISGRI mode) on May 3, 2003. The calibration is made with the use of the Crab nebula observations, as the standard data processing package does not provide adequate calibration tools.

Such spectra are typical for accreting BHs (Sunyaev et al. 1991a,b).

The most straightforward explanation of this spectrum is thermal Comptonisation of soft photons emitted by the inner parts of the disc on relativistic electrons in a hot non-thermal corona above accretion disc. Such coronas are thought to exist in BH X-ray binaries in the low/hard states and disappear (due to effective Compton cooling) when accretion luminosity increases (at the high/soft state). So it is hard to imagine how such a corona could survive a supercritical accretion transition in the case of SS433. It is also problematic to observe directly the hard photons generated in a supercritical accretion disk due to photon trapping effects (e.g. Ohsuga et al. 2003).

Another explanation could be particle acceleration in Poynting-dominated jets in the vicinity of the BH.

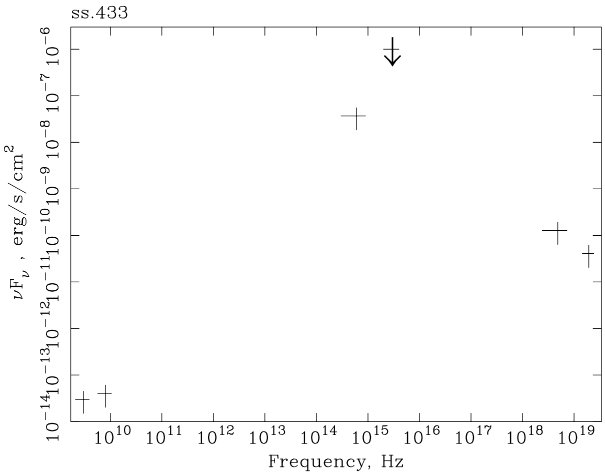

Fig. 6. The total energy spectrum of SS433 in units νF_ν from radio to hard X-rays. The radio, UV and optical data is taken from Gies et al. (2002) and Fender et al. (2000). The interstellar extinction is taken into account ($A_V = 7.5^m$).

The maximum Lorentz-factor of particles in a Poynting dominated outflow is (Michel 1969)

$$\gamma_{max} \sim \sigma^{1/3} \quad (1)$$

where $\sigma = B^2/(4\pi n_e m_e c^2)$ is plasma magnetization parameter (B – magnetic field strength at the jet base, n_e is the electron density). For electron-proton jet launched by a relativistic rotator with circular frequency Ω the magnetization parameter can be rewritten as (see also Camenzind 1990)

$$\sigma = \frac{m_p}{m_e} \frac{B^2 R^2}{\dot{M}_j c} \left(\frac{\Omega R}{c}\right)^2 \quad (2)$$

where $\dot{M}_j = 4\pi n_e m_p R^2 c$ is the mass ejection rate at the jet base. For estimation, near the BH we can put $\Omega R/c \sim 1$ and assume a maximum magnetic field from $B^2/4\pi \sim n_e m_p c^2$. Then $\sigma \sim m_p/m_e \sim 2000$ and $\gamma_{max} \sim 12$. Some additional acceleration can occur outside the fast magnetosonic surface due to a strong photon field ($L_x \sim L_{edd}$) around the jet (Beskin et al. 2003), as the compactness parameter in this case is $l_a = (L/R)\sigma_T/(m_e c^3) \sim 10^3$–$10^4 > \sigma$. This estimate shows that hard (up to 100 keV) X-ray photons can be Compton upscatterred soft X-ray photons from the inner parts of the disk on mildly relativistic electrons accelerated in the Poynting dominated jet formed close to the BH. We stress here that actually observed jet outflow $\sim 10^{-6}\, M_\odot$/yr with $v = 0.26c$ is an order of magnitude larger than the Eddington-controlled matter flux near BH and should be formed around and upstream the initial jet involving non-relativistic disk wind. The observed precession of the jets locked with disk precession firmly indicates that the most jet outflow in SS433 is due to the disk wind. We also note that in the jets, various thermal instabilities can operate giving rise to their inhomogeneous structure. More detailed analysis of rapid variability of SS433 in hard X-rays is in progress.

The total spectrum of SS433 from radio to hard X-rays is shown in Fig. 6. Maximum energy release is in the optical band, as expected from a supercritically accreting disk in which most energy released in the disk is thermalised by the optically thick disk wind. We stress again that the presence of hard X-ray emission from the supercritically accreting disk in SS433 and its variability with precessional period provides evidence for a hollow cone in the polar regions of the disk apparently swept-up in the disk wind by precessing jets.

4. Conclusion

We have presented a quick-look analysis of SS433 by the IBIS telescope onboard the INTEGRAL gamma-ray observatory. The observations revealed for the first time the clear presence of a variable hard X-ray continuum in the SS433 (up to 100 keV). Hard X-rays from supercritical accreting disk around a 10 $M_{\odot}$ BH can be due to Comptonisation of soft X-ray photons generated in the inner disk on relativistic electrons accelerated in the central part of the jet near the BH.

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