Peculiar nature of hard X-ray eclipse in SS433 from INTEGRAL observations

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ABSTRACT

The analysis of hard X-ray INTEGRAL observations (2003–2008) of superaccreting Galactic microquasar SS433 at precessional phases of the source with the maximum disc opening angle is carried out. It is found that the shape and width of the primary X-ray eclipse are strongly variable, suggesting additional absorption in dense stellar wind and gas outflows from the optical A7I component and the wind–wind collision region. The independence of the observed hard X-ray spectrum on the accretion disc precessional phase suggests that hard X-ray emission (20–100 keV) is formed in an extended, hot, quasi-isothermal corona, probably heated by interaction of relativistic jet with inhomogeneous wind outflow from the precessing supercritical accretion disc. A joint modelling of X-ray eclipsing and precessional hard X-ray variability of SS433 revealed by INTEGRAL by a geometrical model suggests the binary mass ratio \( q = m_x/m_v \approx 0.25–0.5 \). The absolute minimum of joint orbital and precessional \( \chi^2 \) residuals is reached at \( q \approx 0.3 \). The found binary mass ratio allows us to explain the substantial precessional variability of the minimum brightness at the middle of the primary optical eclipse. For the mass function of the optical star \( f_v = 0.268 \, M_\odot \) as derived from Hillwig & Gies data, the obtained value of \( q \approx 0.3 \) yields the masses of the components \( m_x \approx 5.3 \, M_\odot \), \( m_v \approx 17.7 \, M_\odot \), confirming the black hole nature of the compact object in SS433.

Key words: binaries: eclipsing – X-rays: binaries – X-rays: individual: SS433.

1 INTRODUCTION

SS433 is a massive close binary system at advanced evolutionary stage (Cherepashchuk 1981, 1989; Margon 1984; Fabrika 2004). This unique galactic X-ray binary with precessing relativistic jets (\( v = 0.26 \, c \), where \( c \) is the speed of light) exhibits several variabilities, including the precessional one (with the period \( P_{\text{prec}} \approx 162 \, \text{d} \)), the eclipsing one (with the binary orbital period \( P_{\text{orb}} \approx 13.08 \, \text{d} \)) and the nutational one (with the nutation period \( P_{\text{nut}} \approx 6.28 \, \text{d} \)) (e.g. Goranskij, Esipov & Cherepashchuk 1998; Davydov, Esipov & Cherepashchuk 2008). SS433 is recognized as a Galactic microquasar with precessing supercritical accretion disc around a compact object, and has been extensively investigated in the optical, radio and X-ray ranges [for a comprehensive review and references, see Fabrika (2004)]. Recent high-resolution optical spectroscopy of the system (Hillwig & Gies 2008) revealed the presence of absorption lines in the spectrum of the optical component identified as a ~A7I supergiant star. Observed orbital Doppler shifts of the absorption lines of the optical component and stationary He\( _n \)) emission allowed Hillwig & Gies to determine the mass ratio of the compact \( (m_x) \) and the optical \( (m_v) \) components in SS433 \( q = m_x/m_v \approx 0.35 \), implying the binary masses \( m_x = 4.3 \pm 0.8 \, M_\odot \) and \( m_v = 12.3 \pm 3.3 \, M_\odot \). Similar values of \( q \), \( m_x \) and \( m_v \) were obtained from the analysis of the optical light curves of SS433 (Antokhina & Cherepashchuk 1987).

The analysis of broad X-ray eclipses in the 1–10 keV range observed by ASCA and Ginga satellites suggests a smaller mass ratio than that obtained from optical spectroscopy and photometry. For example, using X-ray eclipses observed by Ginga, Brinkman, Kawai & Matsuoka (1989) estimated \( q \approx 0.15 \). In their analysis, the authors used the simplifying assumption that the X-ray source is compact and the duration of the X-ray eclipse is fully determined by the size of the optical companion. Ginga light curves at different precessional phases presented in Kawai et al. (1989) were analyzed by Antokhina, Seifina & Cherepashchuk (1992) using the method of binary light-curve synthesis in the model including the precessing accretion disc and jets. They found the possible range of binary mass ratios \( q = 0.15–0.25 \). Using X-ray emission from
SS433 observed by the ASCA satellite (which is mostly produced in precessing thermal jets), Kotani (1998) and Kotani et al. (1998) estimated \( q \approx 0.22 \). Their analysis, with account of uncertainties, allowed, in fact, a fairly broad range of binary mass ratios \( q = 0.06–0.31 \). Thus, the average mass ratio estimate as inferred from the analysis of 1–10 keV X-ray data is smaller (\( q \approx 0.25 \)) than that inferred from optical observations (\( q \approx 0.35 \). However, for \( q < 0.25 \), the total eclipse of the accretion disc by the optical star must occur, so it is hard to explain a significant optical variability of SS433 in the primary eclipse minimum with precessional phase, as in fact observed (Goranskij et al. 1998).

The \textit{INTEGRAL} satellite detected the hard X-ray emission from SS433 up to 100 keV (Cherepashchuk et al. 2003). Our studies of SS433 based on the \textit{INTEGRAL} observations suggested the presence of a hot rarefied corona above the supercritical accretion disc in this source (Cherepashchuk et al. 2005, 2007). The peculiar variability in the shape and width of the primary eclipse in hard X-rays was discovered. The spectral analysis of archival \textit{RXTE} observations of SS433 (Filippova et al. 2006) found evidence for strong variable X-ray absorption which does not support the assumption that the optical star can be considered as an opaque screen with sharp edges at these energies. This implies that the primary eclipse in SS433 is not purely geometrical and that the binary mass ratio as inferred from the analysis of the \textit{Ginga} and ASCA data may suffer from systematic uncertainties.

The results of our previous analysis of the orbital and precessional variability in SS433 observed by \textit{INTEGRAL} (Cherepashchuk et al. 2005, 2007) can be summarized as follows. The hard X-ray flux (25–50 keV) from the source clearly exhibits variability with the precessional period \( P_{\text{prec}} \approx 162.4 \) d from \( \sim 3 \) mCrab at the cross-over phase to \( \sim 18–20 \) mCrab at the maximum disc opening phase (the \( T_1 \) moment, where the moving emission lines in the SS433 spectrum are at maximum separation). Eclipses are observed with the orbital period \( P_{\text{orb}} \approx 13.08 \) d and are very significant. Eclipses observed close to the \( T_1 \) phase (at the precessional phase \( \psi \approx 0 \)) are the deepest ones. The hard X-ray flux (18–60 keV) at the centre of the primary eclipse is still detectable at a level of \( \sim 3 \) mCrab, so the ratio of the maximum un eclipsed flux (\( \sim 20 \) mCrab) to the minimum flux value at the mid-eclipse is about 6–7, which is similar to the amplitude of the precessional off-eclipse hard X-ray variability. The width of the hard X-ray eclipse is found to be larger than that in soft X-rays. The egress out of the hard X-ray eclipse is observed to be strongly variable, most probably due to the absorption of the X-ray flux by accretion flows and asymmetric structured wind from the supercritical accretion disc and by the wind–wind collision region. Similar distortions of the eclipse egress were first observed by \textit{Ginga} (18.4–27.6 keV) (Kawai et al. 1989). The hard X-ray spectrum (20–200 keV) does not change with precessional phase. All these facts suggest that most of the hard X-ray flux of SS433 is generated in a hot extended corona formed in the central parts of the accretion disc. The hot corona may be formed as a result of collision of the wind inhomogeneities with relativistic jets (Begelman, King & Pringle 2006). A more detailed interpretation of the broad-band (3–90 keV) X-ray continuum of SS433 in terms of the multicomponent model including the accretion disc, jet and corona has been given by Krivosheev et al. (2009).

In the present paper, we analyze \textit{INTEGRAL} observations of hard X-ray eclipses of SS433 near the \( T_1 \) moment and interpret them in terms of our multicomponent geometrical model with account of the peculiar shape and strong variability of the primary eclipse and precessional X-ray variability of the source. In Section 2, we describe \textit{INTEGRAL} observations used for the analysis. In Section 2.1, we discuss the precessional variability of SS433. In Section 2.2, we present \textit{INTEGRAL} spectra of SS433 obtained at different precessional intervals and show that they can be fitted by one power law. In Section 2.3, we study in more detail the primary eclipse of SS433 in hard X-rays. Section 3.1 depicts our geometrical model. In Section 3.2, the best-fitting mass ratio is obtained from the joint analysis of eclipsing and precessional light curves. We discuss the obtained results in Section 4 and summarize our findings in Section 5.

## 2 OBSERVATIONS

Dedicated \textit{INTEGRAL} observations of SS433 were carried out in AO-1 for 500 ks, in AO-3 for 500 ks, in AO-4 for 466 ks, in AO-5 for \( \sim 900 \) ks and in AO-6 for \( \sim 500 \) ks. The AO-1 observations (\textit{INTEGRAL} orbits 67–69) were performed at the precessional phase 0 with maximum disc opening. In AO-2, SS433 fell within the field of view (FOV) of \textit{IBIS} when observing the Sagittarius Arm Tangent region, but no X-ray eclipses occurred during this program. In AO-3, SS433 was observed around different precessional phases (\textit{INTEGRAL} orbits 366–369). One X-ray eclipse was partially measured again at the precessional phase close to zero, with an indication of a much narrower eclipse or a sudden mid-eclipse (at the orbital phase \( \phi \sim 1.03 \)) flux increase. Based on these data, the model for the source eclipse has been constructed in Cherepashchuk et al. (2005, 2007); however, these data were not strongly constrained by precessional variability and allowed a broad range of the binary mass ratio \( q \sim 0.1–0.5 \). In AO-4, the source was observed in 2007 May; unfortunately, due to high variability, the source flux was very low, so we exclude these data from the analysis of X-ray eclipses (Set II in Fig. 5). Note the strong increase in the apparent eclipse width. In AO-5, two consecutive eclipses of the source near the zero precessional phase \( \psi = 0 \) were observed in 2007 October. Adding all of these observations allowed us to construct hard X-ray spectra of the source at different precessional phases (Fig. 4). However, the statistics are still insufficient to make orbital phase-resolved spectroscopy. In AO-6, the egress out of the primary eclipse of SS433 was observed in 2008 September (Set V in Fig. 5).

The \textit{INTEGRAL} data were processed with both publically available ISDC software (OSA-7 version) and the original software package written by the Space Research Institute (IKI) \textit{INTEGRAL} team [for the IBIS/ISGRI telescope, see Molko et al. (2004) for more detail]. For the analysis of precessional variability of SS433, we have used both data from our \textit{INTEGRAL} observing program of SS433 and publically available data of all observations where the source was in the FOV of the IBIS/ISGRI telescope (\( <13^\circ \)). The total exposure of the selected data is approximately 8.5 Ms. To perform precessional phase-resolved analysis, we ascribed to each SCW (Science Window or SCW, the natural piece of \textit{INTEGRAL} data – pointing observation with an exposure of \( \sim 2–5 \) ks) the appropriate orbital and precessional phases. The phases are calculated using the ephemeris provided by Fabrika (2004). The orbital primary minimum (corresponding to \( \phi = 0 \)) is

\[
J_{\text{D}1}\text{hel}(\text{hel}) = 2450023.62 + 13.08211E ,
\]

the zero precession phase (corresponding to the \( T_1 \) moment, \( \psi = 0 \)) is

\[
J_{\text{D}2}\text{hel}(\text{hel}) = 2443507.47 + 162.375E .
\]

In Fig. 1 (left-hand panels), we show the exposure distribution of the used observations by phases. For clarity, we presented two cycles. The exposure time distribution over orbital phases is distributed more or less homogeneously, while that over precessional phases.
shows an excess near the $T_3$ moment, since the main part of our SS433 INTEGRAL observing program was focused on observations of the primary eclipses at zero precessional phases where the source flux is maximal.

### 2.1 Precessional variability

In this section, we focused on the precessional phase-resolved analysis of SS433. To exclude the orbital modulation, we have used only observations at orbital phases from the range $0.3 < \phi < 0.7$. After this filtering, we still have $\sim 2.8$ Ms of data distributed across all precessional phases, as shown in Fig. 1 (right-hand panel).

The combined AO1–AO5 data (including those publically available) enabled us to measure, for the first time, the precessional hard X-ray variability (Figs 2 and 3), which turned out to be quite significant and stable over several precessional periods. The maximum-to-minimum flux ratio of the average precessional variability is around 5–7, which is higher than in softer X-ray bands, and suggests the hard X-ray emission originating closer to the base of the visible part of the jets. The eclipsing and precessional variabilities, combined with spectroscopic data simultaneously taken with INTEGRAL observations by the 6-m telescope Spectral Astrophysical Observatory of the Russian Academy of Sciences, were taken into account when attempting to model the light curve of the source by Cherepashchuk et al. (2005). However, the results proved to be inconclusive. First of all, the spectral resolution of the optical observations (around 3000) was insufficient to definitely measure the radial velocity curve of the optical companion. The modelling of X-ray eclipse and precessional variability allowed fairly broad range of parameters, including the mass ratios $q \sim 0.1–0.5$ (primarily due to the lack of reliable observations at the middle of the hard X-ray eclipse). An independent spectral analysis of archival RXTE observations of SS433 (Filippova et al. 2006) also suggested that it is hard to derive the binary mass ratio based on X-ray eclipse observations only.

### 2.2 Hard X-ray spectra

Our previous studies (Cherepashchuk et al. 2003, 2005, 2007) suggested that SS433 is a superaccreting Galactic microquasar with hot corona above the accretion disc which scatters hard X-ray radiation from the central parts of the disc. Out of the eclipse, the source has been reliably detected by IBIS/ISGRI telescope up to 100 keV, with the X-ray continuum fitted by a featureless power-law $dN/d\Omega/dE \sim E^{-2.8}$ photon s$^{-1}$ cm$^{-2}$ keV$^{-1}$ (Cherepashchuk et al. 2003, 2005, 2007) (see Fig. 4).

INTEGRAL observations (2003–2007) were separated into three segments in the precessional phase (Fig. 3) (limited by photon statistics). The resulted spectra are shown in Fig. 4, with no clear difference in the power-law fit in the 20–100 keV energy band. It is recognized from RXTE observations that at softer X-ray band the spectrum is very variable (Filippova et al. 2006), but errors in the first point 18–22 keV of our fit which can be due to this variability have no effect on the value of the power-law fit. One hard X-ray spectral fit at different precessional phases of the accretion disc suggests the presence of a fairly broad hard X-ray emission.
The X-ray continuum spectrum of SS433 in the broad range 3–100 keV can be fitted by a two-component model including thermal X-ray emission from the cooling jet and thermal Comptonization spectrum from the isothermal corona (Krivosheyev et al. 2009). For both un eclipsed and partially eclipsed by the accretion disc corona, the model gives the best spectral fits for $T_{\text{cor}} \simeq 20$ keV with Thomson optical depth $\tau_T \simeq 0.2$, the mass outflow rate in the jet $M_j \simeq 3 \times 10^{19}$ g s$^{-1}$ corresponding to a jet kinetic power of $\sim 10^{39}$ erg s$^{-1}$. These parameters suggest an electron density of $\sim 5 \times 10^{12}$ cm$^{-3}$ at distances $\sim 5 \times 10^{11}$ cm. Such a density is typical in the wind outflowing with velocity $v \sim 3000$ km s$^{-1}$ from a supercritical accretion disc with $M \sim 10^{-4} M_\odot$ yr$^{-1}$ at distances $\sim 10^{11}–10^{12}$ cm from the centre, where the Compton-thick photosphere is formed (Fabrika 2004; Revnivtsev et al. 2004).

Note that despite several primary eclipses having already been observed by INTEGRAL, the measured hard X-ray flux $\sim 5–20$ mCrab from the source is still insufficient for phase-resolved spectral analysis of an individual eclipse. To this aim, additional observations of SS433 by INTEGRAL are planned.

### 2.3 The primary eclipse and its peculiarity

The dedicated INTEGRAL observations of the primary eclipses of SS433 in 2003, 2007 and 2008 were obtained near the $T_3$ precessional phase when the accretion disc is maximally open. The data include the following.

I. INTEGRAL orbits 67–70 (2003 May), precessional phase $\psi = 0.001–0.060$.

II. INTEGRAL orbits 555–556 (2007 May), precessional phase $\psi = 0.980–0.014$.

III. INTEGRAL orbits 608–609 (2007 October), precessional phase $\psi = 0.956–0.990$.

IV. INTEGRAL orbits 612–613 (2007 October), precessional phase $\psi = 0.030–0.064$.

V. INTEGRAL orbits 722–723 (2008 September), precessional phase $\psi = 0.057–0.091$.

The observed eclipses are shown in Fig. 5. In our analysis, we have used only Sets I, III, IV, V and excluded Set II (the one showing the most suppressed egress out of the primary eclipse).

SS433 is known to be a highly variable object at all wavelengths (Cherepashchuk 1989; Fabrika 2004; Revnivtsev et al. 2004, 2006). This is not surprising for a supercritically accreting massive binary, considering various instabilities that should be immanently present in the mass outflow from the optical star and in the accretion disc. It might appear that the primary eclipse of the hard X-ray emission coming from the regions close to the central black hole by the
optical star should be stable. However, it is not the case for hard X-ray eclipse in SS433 (Fig. 5). As seen in this figure, the second eclipse observed in 2007 May (INTEGRAL orbits 555-556) has an unusually broad form: a shallow ingress to and broad egress from the eclipse, which may be due to the low level of uneclipsed X-ray flux from the source $\sim 10$ mCrab. Note that this particular eclipse is very similar to the one observed by Ginga (Kawai et al. 1989). However, already at the next $T_2$ moment in 2007 October (Sets III and IV in Fig. 5), the uneclipsed X-ray flux was at a level of 20 mCrab and the egress from eclipse restored its more familiar form (like in Set I). This effect is particularly clearly visible on the combined X-ray eclipse light curve shown in Fig. 6. The reason for such a strong variability of the hard X-ray eclipse may be related to powerful inhomogeneous gaseous streams feeding the disc and the wind from the supercritical accretion disc. Additional X-ray absorption can be produced in the collision region of the winds from the optical star and the supercritical accretion disc (Cherepashchuk, Bychkov & Seifina 1995).

The slow dense wind from the accretion disc in SS433 should form a Compton-thick photosphere and funnels around relativistic jets (Fabrika 2004). The height of the funnel, $\sim 10^{12}$ cm, comparable to the accretion disc size, can be inferred from the observed $\sim 80$-s lag of the optical emission with respect to the X-rays from the jet base found in the simultaneous optical/X-ray observations of the source (Revnivtsev et al. 2004). Thus, it appears to be quite possible that the variable wind from the precessing supercritical accretion disc causes changes of the funnel structure, so even at the maximum opening disc phase ($T_3$) the shape of hard X-ray eclipse may appreciably vary depending on the accretion rate through the disc. In this connection, it is worth noting the variable broad absorption-like feature that appears immediately after the egress from the eclipse (at orbital phases $\phi \sim 0.15-0.2$; see Fig. 5). It would be very interesting to know whether this feature is due to the true absorption of X-ray emission or just reflects the strong variability of the proper X-ray flux.

We conclude that the hard X-ray eclipse in SS433 is likely to be formed by both geometrical screening of the broad X-ray emitting region by the opaque star and complex gaseous stream and/or inhomogeneous wind from the optical star and the supercritical accretion disc, as well as by the wind–wind collision region. This implies that when fitting the hard X-ray primary eclipse in SS433 by geometrical model, we should use the most stable part of the observed eclipses, i.e. the ingress to the eclipse and the upper envelope of the observed egress out of eclipse. In view of high variability, the analysis of one individual X-ray eclipse only can lead to erroneous determination of the binary system parameters. Moreover, for their reliable determination a joint modelling of both orbital and precessional variability of hard X-ray flux is needed.

3 ANALYSIS OF HARD X-RAY LIGHT CURVES OF SS433

3.1 Geometrical model of SS433

To analyze hard X-ray eclipses of SS433, we used a geometrical model developed earlier for the interpretation of the Ginga data (Antokhina et al. 1992) and the INTEGRAL light curve (Cherepashchuk et al. 2005). We consider a close binary system consisting of a (opaque) ‘normal’ star limited by the Roche equipotential surface and a compact object surrounded by an optically and geometrically thick ‘accretion disc’. Relativistic jets are directed perpendicularly to the disc plane. The ‘accretion disc’ includes the disc itself and an extended photosphere formed by the outflowing wind (Shakura & Sunyaev 1973). The orbit is circular, the axial rotation of the normal star is assumed to be synchronized with the orbital motion.

The disc and ‘jets’ are precessing in space and change the orientation relative to the normal (donor) star. The disc is inclined with respect to the orbital plane by the angle $\theta$. A cone-like funnel is located inside the disc and is characterized by the half-opening angle $\omega$, thus the opaque disc body (see Fig. 7) is described by the radius $r_d$ and the angle $\omega$. The central object is surrounded by a transparent quasi-isothermal homogeneously emitting spheroid with a visible radius $r_j$ and height $b_j$ which could be interpreted as a ‘corona’ or a ‘thick jet’ (without any relativistic bulk motion). Here, $r_j$, $b_j$, and $r_d$ are dimensionless values expressed in units of the binary separation $a$. The radius of the normal star is determined by the relative Roche lobe size, i.e. by the mass ratio $q = m_*/m_b$ ($m_*$ is the mass of the compact object).

Only the ‘corona’ is assumed to emit in the hard X-ray band, while the star and disc eclipse it in the course of the orbital and precessional motion. During precession, the inclination of the disc with respect to the observer changes, causing different visibility conditions for the ‘corona’. The ‘corona’ is partially screened by the cone disc edge, which can qualitatively explain the change of the uneclipsed X-ray flux with precession phase. Observations of the precessional variability can thus be used to obtain a ‘vertical’ scan of the emitting structure, restricting the parameters $b_j$ and $\omega$. The orbital (eclipse) variability observations scan the emitting structure ‘horizontally’, restricting possible values of $r_j$, $\omega$, $q$, and $r_d$. The joint analysis of the precessional and eclipse variability thus enables us to reconstruct the spatial structure of the accretion disc central region, where the hard X-rays are produced, and to estimate the binary mass ratio $q$.

The position of the components of the system relative to the observer is determined by the binary orbit inclination angle $i = 78.8^\circ$, the disc inclination angle to the orbital plane $\theta = 20.3^\circ$ (Margon 1984; Davydov et al. 2008) and the precessional phase $\psi$.

![Figure 7. Geometrical model of the accretion disc and its 'corona'.](https://academic.oup.com/mnras/article-abstract/397/1/479/1007227)
3.2 Results of light-curve analysis

Our model for the orbital and precessional variability of SS433 has the following free parameters: the binary mass ratio \( q = m_2/m_1 \), determining the relative size of the normal star, the disc parameters \( r_d, \omega \) determining the form of the disc, the thick ‘jet’ or ‘corona’ parameters \( r_j, b_j \) determining the form of the hot corona. Note that the X-ray emitting region is qualitatively different for a thin narrow ‘jet’ with \( r_j \ll b_j \sim a \) and a thin short ‘jet’ with \( r_j \ll b_j \ll a \). If \( r_j > b_j \), it is more appropriate to term it as a corona (or a thick ‘jet’). For each value of \( q \) from the range 0.05–1.0, we found other parameters best fitting simultaneously the orbital and precessional light curves. We remind that the precessional light curve was constructed using maximum off-eclipse X-ray flux from the system. The precessional variability amplitude was assumed to be \( A_p \approx 5–7 \). The \( \chi^2 \) criterion was used to evaluate the goodness of fits.

To examine as fully as possible the binary system parameters, we have used different variants of modelling of the observed orbital hard X-ray variability. These included the following.

1. The analysis of light curves consisting of individual points.
2. The analysis of average light curves.
3. The analysis of individual observational sets (I, III and IV–V).
4. The analysis of the combined data from Sets I, III and IV–V.
5. The analysis of the entire eclipse, including the eclipse ingress and (the upper envelope of) egress.
6. The analysis of the ingress to the eclipse only (orbital phases \( \psi = 0.8–1.0 \)).

All methods give similar results. The inferred binary system parameters are found to be sensitive mostly to the form of ingress and the duration of the primary eclipse. The results of the analysis can be summarized as follows.

1. The analysis of individual and average light curves yields similar results (i.e. the use of the average light curve does not add errors to the obtained parameters). This seems obvious, but we directly checked it.
2. The analysis of individual data sets I, III, IV, V and the combined data yields similar results.
3. When searching for the best-fitting model parameters at different \( q \), we found that solutions obtained for the entire primary eclipse (the ingress and the upper envelope of egress) and for the eclipse ingress only are not very different. Taking into account highly variable character of the eclipse egress noted above, below we shall discuss solutions and model parameters obtained from the analysis of the eclipse ingress part only. In the combined primary eclipse (Fig. 6), the ingress part is mostly determined by Sets I and IV.
4. In our previous analysis of the primary orbital eclipse observed by INTEGRAL (Cherepashchuk et al. 2005), we found that for all models the best-fitting values (corresponding to the minimum \( \chi^2 \)) are obtained for the maximum possible radius of the disc \( r_d \) and the maximum possible value of the angle \( \omega \). This conclusion is confirmed here using new data. We also confirm that parameters \( b \) and \( \omega \) are correlated.
5. The minimum deviation of the best-fitting model eclipsing light curve from observed points is reached for the small mass ratio \( q \sim 0.1 \) and a long X-ray emitting ‘jet’ \( (b \gg 0.5) \) with the base radius varying in the wide range \( (r_j \sim 0.05–0.25) \). This means that the ‘jet’ can be long but either thin or thick. However, the main objection to model of the long ‘jet’ comes from its inability to describe the observed precessional variability as shown in Fig. 8. We conclude that at small mass ratio \( q \sim 0.25 \), our model does not simultaneously fit both orbital and precessional variability of SS433 observed by INTEGRAL. The precessional light curve could be fitted at the small mass ratio \( q (0.1) \) by a short X-ray emitting ‘jet’, but then the flux at the centre of the primary eclipse would be zero (Fig. 9), again in contradiction with observations – in all cases, INTEGRAL detects a non-zero X-ray flux of \( \sim 3 \) mCrab at the middle of the hard X-ray eclipse (Fig. 5).
6. For \( q \sim 0.3–0.5 \), our model provides almost similarly good fits to the orbital and precessional variability of SS433. To find the best-fitting value of \( q \), we calculate the sum of the reduced \( \chi^2 \) for the orbital and precessional light curves obtained for the same model parameters: \( \chi^2_{\text{orb}} + \chi^2_{\text{prec}} \) (Fig. 10, panel a). The residuals are minimized relative to four parameters: \( r_d, \omega, r_j, b_j \). The value \( \chi^2_{\text{orb}} \) (Fig. 10, panel b) corresponds to the best-fitting parameters of the orbital light curve for different \( q \). The value \( \chi^2_{\text{prec}} \) is calculated for the corresponding precessional light curve (Fig. 10, panel c). Fig. 10 (panel b) shows that \( \chi^2_{\text{orb}} \) deviations for the orbital eclipse increase with \( q \); there is a quasi-plateau at \( q \sim 0.3–0.5 \), then the
deviations rapidly increase due to a poor fit to the orbital eclipse (especially the eclipse width; see Fig. 12). Fig. 10 (panel c) clearly shows that fits to the precessional light curve get worse sharply for \( q < 0.25 \).

As seen in Fig. 10, the values of the reduced \( \chi^2_{\text{orb}} \) and \( \chi^2_{\text{prec}} \) (minimized relative to four model parameters: \( r_d, \omega, r_j \) and \( b_j \)) are much higher than unity. This means that our model is oversimplified and is not fully adequate to the observational data. The data demonstrate a significant dispersion due to both physical variability of hard X-ray flux and systematic effects of absorption by gaseous streams in the wind–wind collision region, which we do not take into account in our model. So, we cannot rigorously estimate the confidence region of the sought parameter \( q \). When the reduced \( \chi^2 > 1 \), it is generally accepted to give only the optimal value of the sought parameter without quoting the confidence range since the latter cannot be statistically justified. The absolute minimum of the residuals \( \chi^2_{\text{tot}} \simeq 8.21 \) is reached at \( q \simeq 0.3 \), so we accept it as the optimal value. Nevertheless, as the reduced residuals \( \chi^2_{\text{orb}} \) and \( \chi^2_{\text{prec}} \) strongly change with \( q \) (Fig. 10), it appears meaningful to consider the mass ratio \( q \) from the range \( 0.25-0.5 \). The lower limit of the mass ratio interval is determined by the abrupt increase in the precessional \( \chi^2_{\text{prec}} \) residuals for \( q < 0.25 \). The upper limit is determined by (less abrupt) increase in \( \chi^2_{\text{orb}} \) residuals for \( q > 0.5 \).

Therefore, our simple geometrical model of SS433 suggests an acceptable range of binary mass ratio of \( 0.25 \leq q \leq 0.5 \). The absolute minimum of the total reduced residuals \( \chi^2_{\text{tot}} \simeq 8.21 \) at \( q \simeq 0.3 \) agrees well with the mass ratio estimate \( q \simeq 0.35 \) obtained by Hillwig & Gies (2008). We stress that the latter estimate is obtained from optical spectroscopy of SS433 and is in agreement with the estimate \( q \simeq 0.4 \) derived by Antokhina & Cherepashchuk (1987) from the analysis of optical eclipse light curves at different precessional phases. Our new binary mass ratio estimate \( q \simeq 0.3 \) is obtained from independent observations in hard X-rays. Such a good convergence of the mass ratio estimates found from different and independent observational data strengthens the reliability of the found binary mass ratio value \( q \simeq 0.3 \).

The best-fitting model parameters for \( q \simeq 0.3 \) (see Fig. 11) correspond to an extended oblate coronal with width comparable to the size of the accretion disc \( r_j \simeq r_d \) and small vertical height \( b_j \sim 0.15-0.20 \). In the framework of our model, such a geometry of the hard X-ray emitting region is caused by the wide primary eclipse minimum and large amplitude of the precessional variability. The precessional light curve in hard X-rays is shaped by the outer parts of the disc eclipsing the high-temperature corona that scatters thermal X-rays from jets and possibly the innermost accretion disc (Krivosheyev et al. 2009).

Fig. 11 shows the orbital and precessional light curves for the optimal binary mass ratio \( q = 0.3 \). For comparison, best-fitting model light curves for mass ratio \( q = 0.6 \) and 0.8 are presented in Figs 12 and 13, respectively. Figs 8, 9, 11, 12 and 13 show the change in the primary eclipse minimum width for different binary mass ratios. Clearly, the model best fit to the form and width of the
Our analysis confirms that SS433 is a superaccreting microquasar with black hole. The obtained high value of the best-fitting binary mass ratio in SS433 $q \simeq 0.3$ allows us to explain a substantial amplitude ($\sim 0.5$ mag) of the optical variability at the minimum of the primary eclipse with precessional phase. The orbital inclination of SS433 is known from independent analysis of moving emission lines ($i \simeq 78.8$; Margon & Anderson 1989), so at low-mass ratios $q < 0.25$, the small relative radius of the Roche lobe of the compact object should have caused the total eclipse of the bright precessing accretion disc around the compact object by the optical A7I star, implying a constant optical flux at the centre of the eclipse at different precessional phases. This contradicts observations (see e.g. Goranskij et al. 1998). At $q = 0.3$–0.5, the size of the Roche lobe of the compact object is relatively large to cause only partial primary optical eclipse of the accretion disc by the A7I star at all precessional phases, which leads to a notable precessional variability of the minimum brightness at the middle of the primary eclipse.

A small value of the binary mass ratio was found by Kawai et al. (1989) from the analysis of soft (1–10 keV) X-ray eclipses of SS433. The modelling of broad-band X-ray spectrum of SS433 shows that in this energy range thermal emission of relativistic jets with temperature decreasing along the jet dominates (Filippova et al. 2006; Krivosheyev et al. 2009). The observed broad width of the soft X-ray eclipse was interpreted by Kawai et al. (1989) in terms of purely geometrical model of the eclipse of jets by the optical star with sharp limb, yielding a small value of the binary mass ratio $q = 0.15$. The observed independence of the soft X-ray eclipse width on energy has been the main argument justifying this model and hence the inferred low value of the mass ratio. However, this argument holds only if the temperature along jets does not change with distance from the compact object. In fact, it decreases along jets (unless some additional heating mechanism is assumed), so at energies $\sim$10 keV central parts of the jets are eclipsed. Consequently, the duration of purely geometrical eclipses must be longer at 10 keV than at $\sim$1 keV where cooler periphery of the jets is eclipsed (Filippova et al. 2006). The independence of the X-ray eclipse duration on energy in the 1–10 keV range can be due to the compensation of the effect of decreasing temperature along jets and the increase of soft X-ray absorption in the extended atmosphere of the optical star, which is clearly seen in the RXTE observations (Filippova et al. 2006). So, the effective radius of the eclipsing star increases at lower energies. This explains the constant width of X-ray eclipse in the 1–10 keV energy range. Turning this argument around, the constant width of the X-ray eclipse in the 1–10 keV may imply that the eclipsing A7I star in SS433 does not have a sharp limb, so that X-ray eclipses in SS433 may not be purely geometrical and can be affected by extinction in strong stellar wind from the optical star. This lends additional support to our interpretation of X-ray eclipses in SS433, making use of the upper envelope of variable eclipsing hard X-ray light curve.

Our analysis of the primary hard X-ray eclipse of SS433 at the precessional phase $\psi \simeq 0.05$ with account for precessional variability of the off-eclipse flux suggests the optimal binary mass ratio $q = m_x/m_1 \simeq 0.3$. From spectroscopic observations of SS433 carried out by Hillwig & Gies (2008), a semi-amplitude of the radial velocity curve of the optical A7I component was determined: $K_1 = 58.2 \pm 3.1$ km s$^{-1}$. Combining it with semi-amplitude of the radial velocity curve of the compact component $K_c = 168 \pm 18$ km s$^{-1}$ (Hillwig et al. 2004) and the binary inclination angle $i = 78.8$ (Margon & Anderson 1989; Davydov et al. 2008), we obtain for the mass function of the optical component of SS433

$$f_0(m) = \frac{m_x \sin^3 i}{(1 + 1/q)^2} \simeq 0.268 M_\odot$$

\hspace{1cm} (1)
and the spectroscopic mass ratio $q \simeq 0.35$. This allows us to estimate masses of the compact object and the optical star for $q \simeq 0.3$:

$$m_1 \simeq 5.3\, M_\odot, \quad m_2 \simeq 17.7\, M_\odot.$$  

(2)

With the derived mass function of the compact star $f_c(m) = 0.268\, M_\odot$, the binary mass ratio range $q = 0.25$–0.5 obtained from our analysis allows the mass range of the compact star $7.1$–$2.56\, M_\odot$. The lower mass limit for $q = 0.5$ formally admits a neutron star as the compact object in SS433. However, the optimal value $q \simeq 0.3$ independently obtained from the analysis of hard X-ray eclipses and precessional variability fully agrees with the mass ratio value $q = 0.35$ found by Hillwig & Gies (2008) from optical spectroscopy. So, we conclude that the compact object in SS433 is highly unlikely to be a neutron star and is indeed a black hole.

The mass of the black hole in SS433 $m_2 \simeq 5\, M_\odot$ is strongly based on its mass function derived from the optical spectroscopy (Hillwig & Gies 2008). The value of the mass function is very sensitive to the radial velocity semi-amplitude of the optical star $K_\star$. As we emphasized earlier (Cherepashchuk et al. 2005), the measured semi-amplitude can be affected by the X-ray heating effect of the optical star, since we ascribe the observed radial velocity amplitude to the centre of mass of the optical star filling its Roche lobe. The effect decreases with the binary mass ratio $q$. Although no signatures of the X-ray illumination effect on the radial velocity amplitude was found by Hillwig & Gies (2008), the obtained semi-amplitude $K_\star$ and hence the derived mass function of the compact star in SS433 should be treated with some reservation. Clearly, new high-resolution optical spectroscopy of SS433 is in order to accurately measure the radial velocity curve of the optical star.

5 CONCLUSIONS

The discovery of strong variability of the hard X-ray eclipse at precessional phases corresponding to the maximum disc opening angle for the observer and regular significant precessional variability are the main findings of our INTEGRAL observations of SS433. It is shown that the duration of the primary X-ray eclipse at different epochs changes by almost two times and the amplitude of the precessional variability is five to seven times. This implies that X-ray eclipses in SS433 are not purely geometrical; they are shaped by absorption in a powerful stellar wind and gas streams from the optical star, as well as in the wind–wind collision region. So, to infer the binary mass ratio $q$ from the analysis of X-ray eclipses, we have used only the ingress to and upper envelope of egress out of the primary eclipse. The joint analysis of eclipsing light curve and the regular precessional light curve for off-eclipse flux from the system yielded the mass ratio estimate $q \simeq 0.25$–0.5. The relatively high value of the binary mass ratio $m_1/m_2$ (and hence the relatively large size of the Roche lobe of the compact star) suggests an explanation to peculiarities of the optical variability of SS433, in particular to the observed substantial precessional variability of the minimum brightness at the middle of the primary optical eclipse.

Using the mass function of the optical star found by Hillwig & Gies (2008), $f_c(m) = 0.268\, M_\odot$ and the value of $q = m_1/m_2 \simeq 0.3$ corresponding to the absolute minimum of $f_c^*$ residuals, we concluded that the masses of binary components of SS433 are $m_1 \simeq 5.3\, M_\odot, m_2 \simeq 17.7\, M_\odot$. The high mass of the compact object leaves no doubts that it is a black hole.

The independence of the hard X-ray spectrum on the accretion disc precessional phase suggests that the hard X-ray emission ($kT = 20$–$100\, \text{keV}$) is formed in an extended, hot, quasi-isothermal corona. The heating of the corona can be related to the transformation of the kinetic energy of relativistic jets to an inhomogeneous wind outflow from the precessing supercritical accretion disc (Begelman et al. 2006).

The Monte Carlo simulations of broad-band X-ray spectrum of SS433 at the maximum disc opening precessional phases (Krivosheev et al. 2009) allowed us to determine the main physical characteristics of the hot corona (temperature $T_{\text{cor}} \simeq 20\, \text{keV}$, Thomson optical depth $\tau \simeq 0.2$), as well as to estimate the mass outflow rate in jets $M_\text{j} = 3 \times 10^{39}\, \text{g}\,\text{s}^{-1}$ yielding the kinetic power of the jets $\sim 10^{39}\, \text{erg}\,\text{s}^{-1}$.

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