COORDINATED INTEGRAL AND OPTICAL OBSERVATIONS OF SS433

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ABSTRACT

Results of simultaneous INTEGRAL and optical observations of galactic microquasar SS433 in May 2003 are presented. The analysis of the X-ray and optical eclipse duration and hard X-ray spectra obtained by INTEGRAL together with optical spectroscopy obtained on the 6-m telescope allows us to construct a model of SS433 as a massive X-ray binary. X-ray eclipse in hard X-rays has a depth of ~ 80% and extended wings. The optical spectroscopy allows us to identify the optical companion as a A5-A7 supergiant and to measure its radial velocity semi-amplitude $K_v = 132 \text{ km/s}$. A strong heating effect in the optical star atmosphere is discovered spectroscopically. The observed broadband X-ray spectrum 2-100 keV can be described by emission from optically thin thermal plasma with $kT \sim 15 - 20 \text{keV}$.

Key words: INTEGRAL; SS433; X-rays; optical spectroscopy.

1. INTRODUCTION

SS433 is a supercritically accreting microquasar with precessing accretion disk and collimated mildly relativistic ($v \approx 0.26c$) jets (see e.g. Cherepashchuk et al. 1996 and references therein). Since the discovery in 1978, this unique massive X-ray binary system has been investigated in optical, radio and X-rays by many authors (e.g. Cherepashchuk 1981, Margon 1984, Kawai et al. 1989, Kotani et al. 1996, Goranskii et al. 1998a,b, Marshall et al 2002, Fabrika 2004).

SS433 is highly variable system and shows different types of periodicities:

1. Precessional variability ($P_{precc} = 162^d.5$) which is observed by periodical Doppler-shifts of H, He I, Fe XXV and other X-ray emission lines in optical and X-ray spectra and is clearly visible in optical and X-ray light curves.

2. Orbital periodicity ($P_{orb} = 13^d.082$). The shape of the orbital optical light curve strongly changes with precession phase (Goranskii et al. 1998 a,b, Cherepashchuk and Yarikov 1991). The value of the orbital period remains stable over more than 30 years, which can be considered as an argument against the common envelope model for SS433.

3. Nutation periodicity ($P_{nut} = 6^d.2877$) which is observed as periodic deviations from purely precessional Doppler motion of emission lines and can be recovered from photometric data (Goranskii et al. 1988 a,b, Cherepashchuk and Yarikov 1991). The period and phase of the nutational variability remain stable over at least 16 years (around 950 nutation periods). Nutation radial velocity variations are delayed from the nutation photometric variability by 0.6 days, which corresponds to the travel time from the accretion disk center to the formation region of optical moving emission lines downstream the relativistic jets located at $l \approx 10^{14} - 10^{15}$ cm away from the disk center.

The AO-1 INTEGRAL observations of SS433 discovered hard (up to 100 keV) X-ray spectrum in this supercritically accreting microquasar (Cherepashchuk et al. 2003), suggesting the presence of an extended hot (with temperature up to $10^8 \text{ K}$) region at the central parts of the accretion disk. These new data made it possible to compare the eclipse characteristics of SS433 at different energies: soft X-rays (2-10 keV, the ASCA data), soft and medium X-ray (1-35 keV, the Ginga data), hard X-ray (20-70 keV, the INTEGRAL data), and optical. Such a comparison allows us to study the innermost structure of the su-
Figure 1. IBIS/ISGRI spectrum of SS433 collected over INTEGRAL orbits 67-69 in May 2003. The best fit (solid line) is for exponential cut-off with $kT = 14\pm2$ keV (reduced $\chi^2 = 0.32$ for 7 dof, CL ≈ 95%).

Figure 2. RXTE PCA and IBIS/ISGRI spectrum of SS433 obtained during simultaneous RXTE/INTEGRAL observations of SS433 in March 2004 (JD 2453076-2453078). The best fit (solid line) is for emission from optically thin plasma with $kT = 19.5\pm1$ keV.

Figure 3. IBIS/ISGRI 20-40 keV (upper panel) and 40-70 keV (bottom panel) count rates of SS433 (without background subtraction). The egress part of the X-ray eclipse was kindly provided by Diana Hannikainen.

2. OBSERVATIONAL CAMPAIGN

The coordinated multiwavelength observational campaign of SS433 was organized during the AO-1 INTEGRAL observations of the SS433 field in March-June 2003 with the participation of the following research teams.

1. Special Astrophysical Observatory of Russian Academy of Science (SAO RAS) (S. Fabrika, E. Barsukova). Provided high signal-to-noise optical spectroscopy of SS433 at the 6-m telescope.

2. Crimean Station of Sternberg Astronomical Institute (V. Lyuty, T. Irsmambetova). Made BVR-photometry at the 0.6-m telescope.

3. Kazan State University. Performed optical photometry at the Russian-Turkish 1.5-m telescope RTT-150 at the TUBITAK National Observatory, Turkey (I. Bikmaev, N. Sakhibullin).

4. Infrared K-photometry was performed at 1.1-m AZT-24 telescope of Pulkovo Observatory in Italy, Observatore di Campo Imperatore (Yu. Gnedin, A. Arkharov, V. Larionov).

5. Radio monitoring at cm wavelength has been performed at the RATAN-600 radio telescope of SAO RAS, indicating the source to be at its non-flaring state (see Trushkin 2003 for more detail).

The results of a quick-look analysis of the INTEGRAL observations of SS433 were published earlier (Cherepashchuk et al. 2003). Here we present the results of more detailed study of the INTEGRAL data together with the simultaneous optical spectroscopic and photometric observations of SS433. More complete studies of all data on SS433 obtained during this campaign will be reported elsewhere.

3. IBIS/ISGRI LIGHT CURVES AND SPECTRA

The INTEGRAL IBIS/ISGRI data were analyzed using publically available ISDC software (OSA-3 version). The main results are as follows.

3.1. The IBIS/ISGRI spectrum of SS433 (25-100 keV) obtained in May 2003 can be equally well fitted both by a power-law $\sim E^{-\alpha}$ with photon index $\alpha \approx 2.7\pm0.13$ or optically thin thermal plasma emission with $kT \sim 12-16$ keV (Fig. 1). The source was not significantly detected by the Jem-X telescope during these observations. However, we
3.2. No rapid variability was found in the hard X-ray band on characteristic timescales \( \leq 1 \) hour.

3.3. The IBIS/ISGRI count rates of SS433 are presented in Fig. 3. The X-ray eclipse at hard energies is observed to be a little narrower than the optical one, slightly broader than in the 1-35 keV energy range and display extended wings (Fig. 4). This is opposite to what is found in ordinary eclipsing X-ray binaries (like Cen X-3, Vela X-1 etc.), in which the X-ray eclipse duration decreases with energy. This new fact may reflect a complicated structure of the innermost supercritical accretion disk in SS433.

3.4. The eclipse depth is about 80% in hard X-rays compared to \( \sim 50\% \) in 6-10 and 5-28 keV band (Fig. 4).

3.5. The 25-50 keV X-ray flux increases from \( \sim 5 \) to \( \sim 17 \) mCrab during precession period in March-May 2003. This modulation is 1.5-2 times larger than observed in 2-10 keV energy band. Thus, both precessional and eclipsing hard X-ray variabilities in SS433 exceed by 1.5-2 times those in the standard X-ray band. This suggests a more compact hard X-ray emitting region in the central parts of the accretion disk.

The observed X-ray eclipse was interpreted by the model of a close binary with thick precessing accretion disk (Antokhina et al. 1992). The model includes the following basic elements: i) Dark optical star filling its Roche lobe. ii) Dark thick precessing accretion disk with a central cone-like region (the cone angle \( \sim 60^\circ \)). iii) Bright extended bulge located at the central cone of the accretion disk. The observed X-ray eclipse in the 25-50 keV band is best fitted by this model for the mass ratio \( q = m_x/m_v \approx 0.3 \) and the bright bulge size \( \sim 0.3a \), where \( a \approx 85R_\odot \) (for \( q = 0.3 \)) is the binary semi-major axis (Fig. 5). However, for reasons discussed below we shall assume \( q = 0.3 \) as a fiducial value.
4. OPTICAL OBSERVATIONS

4.1. Optical photometry

Photometry of SS433 was performed simultaneously with INTEGRAL observations by the Russian-Turkish RTT-150 telescope of Kazan University at the TUBITAK National Observatory, Turkey. Observations were made by using commercial, Thermoelectrically cooled to -60 C ANDOR firm CCD (model DW436, www.andor-tech.com) provided for RTT150 by MPA. Low noise back-illuminated EEV chip has 2048 x 2048 pixels of 13.5 mkm size each. Full field of view is 8 x 8 arcmin with frame reading time of 40 sec at 2 x 2 binning. To increase the time resolution only parts of the field of view with reference stars N 1,2,3,4,5 (Leibowitz and Mendelson, 1982) around SS433 were stored to PC. The obtained V-light curve is presented in Fig. 6. Strong (~ 0.15 mag) intranight variability of the source on timescales ~ 100 s - 100 min is clearly detected. The mean V light curve during the eclipse obtained at the Crimean Laboratory of SAI simultaneously with the INTEGRAL observations is also shown in Fig. 6. The optical eclipse minimum is observed at $JD = 2452770.863$, as predicted by the orbital ephemeris given by Goranskii et al. 1998a.

4.2. IR-photometry

Near IR observations of SS433 were obtained at the AZT-24 1.1m telescope in Campo Imperatore (Italy) with SWIRCAM during a period spanning July-August 2003. SWIRCAM is the infrared camera that incorporates a 256x256 HgCdTe NIGMOS 3-class (PICNIC) detector at the focus of AZT-24. It yields a scale of 1.04/pixel resulting in a field of view of 4x4 sq. arcm. The observations were performed through standard JHK broadband filters. The NIR monitoring of SS433 started several orbits after the INTEGRAL observations. The JHK light curves obtained in July-August 2003 are presented in Fig. 7. The observations were done close to the cross-over precessional phase, where the orbital modulation appears to be significantly reduced.

4.3. Optical spectroscopy

The optical spectroscopy of SS433 was carried out at the 6-m telescope of SAO RAS during 6 nights in April 28 and May 9-13 2003, simultaneously with the INTEGRAL observations, at the precessional phase corresponding to the maximum disk opening angle. The long-slit spectrograph and PM-CCD 1000x1000 detector were used to obtain 4100-5300 A spectra with a resolution of 3 A (1.2 A/pix). The blue part of the optical spectrum including He II 4686 emission line was chosen for the analysis. The standard technique was used for spectral reduction and calibration. Fig. 8 shows four spectra of supergiants with known temperatures (Le Borgne et al. 2003) and SS433 spectra averaged over nights 28/04/03 and 11/05/03 (the disk eclipse phase) (second from the top spectrum in the figure) and over 09/05/03 and 12/05/03 (corresponding to evenly spaced from...
Figure 8. Optical spectra of SS433 taken on the 6-m telescope and spectra of supergiants of known temperatures (Le Borgne et al. 2003) for a comparison. Two upper spectra are averaged over nights 28/04/03 and 11/05/03 (the disk eclipse phase) (second from the top spectrum in the figure) and over 09/05/03 and 12/05/03 (corresponding to evenly spaced from the eclipse center orbital phases 0.88 and 0.12) (the top spectrum).

Figure 9. Evolution of absorption lines in the optical spectra of SS433 taken at different orbital phases. For comparison, spectra of 8400 K and 20000 K supergiants are shown in the bottom. Orbital evolution of blends and radial velocities are traced by different absorption lines (dashes). See the text for more detail.
Figure 10. Radial velocity curve of the optical companion of SS433 obtained from 4 individual absorption lines over 6 nights.

the eclipse center orbital phases 0.88 and 0.12) (the top spectrum). Spectral resolution in SS433 spectra and in those of standard supergiants is the same. The signal-to-noise ratio in our spectra is $> 60$ at $\lambda 4250$ Å per resolution element. Fe II 4233 emission is seen, emission lines in SS433 spectrum are broad ($FWHM \sim 10$ Å). CII 4267 and NIII 4196,4200 + HeII 4200 emissions are also marginally present. In the Figure, the absorption lines seen out of the eclipse are marked with short vertical bars; those which are seen in the eclipse or present in both spectra are marked with long bars.

The intensity of absorption lines during the eclipse allows us to estimate the effective temperature of the optical star to be $T < 9000$ K. The relative intensities of the strongest absorption lines indicate $T = 8000 \pm 500$ K, implying the optical spectral class of the companion A5-A7I.

The heating effect of the companion atmosphere is discovered by absorption lines. During the disk eclipse egress, low-excitation absorption lines strongly weaken. The stellar hemisphere illuminated by the bright accretion disk probably has a temperature of $\sim 20,000$ K, as the presence of CII 4267 absorption suggests. This is the only strong line in this region in hot stars. The CII 4267 absorption is deep out of the eclipse (Fig. 8) and the line is only marginally detected inside the eclipse phases. Evolution of the blend 4273 (FeI 4271.8 + FeII 4273.3 + CrII 4275.6) is seen: in the eclipse, low-excitation line FeI is strongest, while out of eclipse FeII+CrII lines enhance. Also, other FeI lines appear only in the eclipse. These effects are illustrated better by Fig. 4 in which spectra of standard stars with different effective temperatures are shown together with spectra of SS433 obtained in 9/05, 10/05, 28/04+11/05, 12/05 and 13/05 (orbital eclipses fell in nights 10/05 and 28/04+11/05).

In Fig. 10 we present individual absorption line radial velocities for four best-suited lines averaged over one night, as a function of the orbital phase for 6 nights. It is important to note that the strongest lines (FeII, HeI, hydrogen) are present in SS433 spectrum as emissions. Some other strong lines (among FeII and HeI lines) appear in SS433 as P Cyg-like absorption components or distorted absorptions, they are disfavored for the optical star radial velocity analysis, as they most probably form in the powerful outflowing disk wind (Fabrika et al. 1997).

The radial velocity curve measured by the most reliable collection of 22 absorption lines in the spectral range 4200-5300 Å is shown in Fig. 11. Note that the absorption lines in SS433 spectrum are seen at our spectral resolution as blends containing 1-3 strong lines. Relative intensities of the lines are probably change from date to date through the eclipse. In this reason we measured only those lines and in only those dates where the lines were detected the most convincingly. The radial velocity (Fig. 11) has been obtained by coadding of radial velocity curves of individual lines and a radial velocity of all lines for 11/05/03 (the orbital phase 0.048) was adopted to be a zero. The derived radial velocity semi-amplitude of the optical star is $K_v = 132 \pm 9$ km/s, the gamma-velocity of the binary system is $v_\gamma = 14 \pm 2$ km/s. The absorption line radial velocity transition through the $\gamma$-velocity occurs at the middle of the optical eclipse ($\phi_b = 0.07$), confirming that the lines actually belong to the optical star.

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These results confirm the earlier determination of $K_v$ by Gies et al. (2002) also made at the maximum disk opening angles (note that spectroscopic observations by Charles et al. 2004 were performed at the crossover phase of SS433 when the accretion disk is seen edge-on; such a phase is disfavored for the optical star radial velocity analysis as strong gas outflows are present in the disk orbital plane; selective absorption in this moving gas affects the true radial velocity of the optical star).

The heating effect of the optical star also distorts the radial velocity semi-amplitude. The analysis (Wade...
Comparison of radial velocities of the accretion disk \((K_x = 175 \text{ km/s, Fabrika and Bychkova 1990})\) and optical star \((K_v = 132 \text{ km/s})\) yields the mass ratio in the SS433 system \(q = m_x/m_v = K_v/K_x = 0.75\). This is an upper limit, as the true value of \(K_v\) should be corrected for the heating effect. Taken at face value, these \(q, K_v\), lead to the optical star mass function \(f_v \approx 3.12M_\odot\) and the binary component masses \(m_x = 18M_\odot\), \(m_v = 24M_\odot\). However, such a big mass ratio is in a strong disagreement with the observed duration of X-ray eclipse, which suggests much smaller mass ratio \(q \sim 0.2-0.3\). We stress that the binary inclination angle in SS433 \((i = 78^\circ 8)\) is fixed from the analysis of moving emission lines.

There are two possibilities: (1) either the model we used to fit X-ray eclipses should be modified, or (2) the value of \(K_v\) and \(K_x\) are influenced by additional physical effects. Though there are some reasons to modify the model (e.g., asymmetric shape of the X-ray eclipse, which may suggest an asymmetric wind outflow from the illuminated part of the optical star), we shall consider here only the second possibility. We repeat again that the actual value of \(K_v\) should be decreased to account for the observed heating effect.

Let us assume the mass ratio in the system to be \(q = 0.3\), as with this value we can satisfactorily describe the X-ray eclipse width (see Fig. 4). Taking \(K_v = 132 \text{ km/s}\) yields \(f_v \approx 3.1M_\odot\) and \(m_x = 62M_\odot\), \(m_v = 206M_\odot\), \(K_x = 440 \text{ km/s}\). Clearly, this is an unacceptable model. Now let us decrease \(K_v\) down to 85 km/s, the lower limit which follows from more accurate treatment of the heating effect in the radial velocity curve analysis (Wade and Horne 1988, Antokhina et al. 2004). This would yield a better fit with \(m_x = 17M_\odot\), \(m_v = 55M_\odot\), and \(K_x = 283 \text{ km/s}\), still too high to be acceptable. Finally, let us take into account that less than half of the stellar surface is sufficiently cool to give the absorption lines under study (e.g., due to sideways heating from X-ray jets and scattered UV radiation in the strong accretion disk wind). This additionally decrease the value of the actual radial velocity semi-amplitude. So taking, for example, \(K_v = 70 \text{ km/s}\) and \(q = 0.3\) yields the optical star mass function \(f_v \approx 0.46M_\odot\) and binary masses \(m_x = 9M_\odot\), \(m_v = 30M_\odot\) and optical star radius \(R_v \sim 40R_\odot\). This radius is compatible with typical bolometric luminosity of a \(30M_\odot\) A5-A7 supergiant with \(T_{eff} \sim 8500 \text{ K}\). In this solution, \(K_x \geq 233 \text{ km/s}\), larger than the measured value 175 km/s, but the true value of \(K_x\) may be affected by the strong accretion disk wind.
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