On the Change of the Inner Boundary of an Optically Thick Accretion Disk around White Dwarfs Using the Dwarf Nova SS Cyg as an Example

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Abstract — We present the results of our studies of the aperiodic optical flux variability for SS Cyg, an accreting binary system with a white dwarf. The main set of observational data presented here was obtained with the ANDOR/iXon DU-888 photometer mounted on the RTT-150 telescope, which allowed a record (for CCD photometers) time resolution up to 8 ms to be achieved. The power spectra of the source’s flux variability have revealed that the aperiodic variability contains information about the inner boundary of the optically thick flow in the binary system. We show that the inner boundary of the optically thick accretion disk comes close to the white dwarf surface at the maximum of the source’s bolometric light curve, i.e., at the peak of the instantaneous accretion rate onto the white dwarf, while the optically thick accretion disk is truncated at distances $8.5 \times 10^9 \text{ cm} \sim 10R_{\text{WD}}$ in the low state. We suggest that the location of the inner boundary of the accretion disk in the binary can be traced by studying the parameters of the power spectra for accreting white dwarfs. In particular, this allows the mass of the accreting object to be estimated. Key words: accretion disks, fast variability, optical observations

INTRODUCTION

Compact objects in binary systems (white dwarfs, neutron stars, black holes) form accretion disks around themselves from the matter coming into the region of dominance of their gravity (see, e.g., Frank et al. 2002). Moving toward the compact object, the matter in the accretion disk releases gravitational energy and heats up to high temperatures, radiating in the optical, ultraviolet, and X-ray bands (see, e.g., Shakura and Sunyaev 1973). It has long been pointed out that the accretion flow around compact objects can be inhomogeneous and consist of several regions with significantly differing physical properties, for example, optically thick and optically thin/corona regions (Shapiro, Lightman and Eardley, 1976; Ichimaru, 1977; Poutanen and Svensson, 1996; Done et al., 2007).

The so-called dwarf novae, accreting white dwarfs in binary systems with low-mass Roche-lobe-filling companion stars, are among the best-studied systems with accretion disks. An ever-increasing set of measurements exists for them, suggesting that the accretion disk in some states of the binary system is not optically thick over its entire extent (Pringle, Verbund and Wade, 1986; Livio and Pringle, 1992; King, 1997; Gänsicke et al., 1999; Belle et al., 2003; Linnell et al., 2005). In such states, the optically thick accretion disk ends at a certain distance from the white dwarf within which the flow becomes optically thin. Both the interaction with the white dwarf magnetosphere, if the white dwarf has a sufficiently strong magnetic field (Patterson, 1994, Belle et al., 2003), and gradual evaporation of the accretion disk (Meyer and Meyer-Hofmeister, 1994) can be responsible for this transition.

However, the current status of the accretion disk models does not allow the radius at which the optically thick flow evaporates to be predicted with confidence (see, e.g., Meyer-Hofmeister and Meyer, 2001). Thus, the question about the truncation (evaporation) of the inner parts of the accretion disks has not been ultimately resolved. An additional reliable measurement of the inner radii for the accretion disks of accreting systems in various states would be an important confirmation of the validity of the existing model for the accretion flow in binary systems.

Recently, it has been shown that the inner boundary of the optically thick disk can be estimated by analysing the power spectrum of aperiodic noise in the accreting source (Revnivtsev et al., 2009, 2010). In this paper, we applied this method to determine the radius at which the accretion disk in SS Cyg, a binary system with an accreting white dwarf...
dwarf, is truncated.

APERIODIC NOISE OF ACCRETING SOURCES FOR DIAGNOSING THE GEOMETRY OF ACCREPTION FLOWS

It has been known almost since the discovery of accreting binary systems that, as a rule, they exhibit aperiodic flux variability in a wide range of time scales—flickering (see, e.g., Linnell 1950; Bruch 1992).

As recent studies have shown, a modulation of the instantaneous accretion rate at different distances from the central object and their subsequent multiplicative addition (the so-called model of propagating fluctuations Lyubarskii 1997; Churazov et al. 2001) are the most probable mechanisms of flickering in the light curves of accreting systems. In this model, a variable emission is generated in the central regions of the accretion flow (which is confirmed, for example, by the curves of the variability amplitude in eclipsing systems (see Bruch 2000; Baptista, Bortotetto 2004) for accreting white dwarfs and is shown by the fast (up to time scales of the order of tens of milliseconds) variability of the large fraction of their X-ray flux for accreting neutron stars and black holes). However, the accretion flow itself is modulated at various (including) large distances from the compact object as a result of the stochastic nature of viscosity in accretion disks (see, e.g., Balbus, Hawley 1991; Brandenburg et al. 1995; Hirose et al. 2006), with the variations on shorter time scales that emerge in the inner disk regions modulating the accretion rate of the matter coming into this region from the outer regions.

In this model, the emerging broadband power spectrum must have features in the range of frequencies corresponding to the characteristic time scales at the accretion disk edges. In particular, the truncation of the accretion disk in its central part in the model of propagating fluctuations must lead to a break in the variability power spectrum: the source’s flux variability must be suppressed at higher frequencies relative to the situation where the accretion disk is not truncated. As the inner disk boundary moves toward the compact object, the break frequency must, accordingly, increase.

An observational confirmation of this prediction was given previously by Revnivtsev et al. 2009. In particular, it was shown that accreting magnetized neutron stars (X-ray pulsars) whose radius of the magnetosphere (which determines the inner boundary of the optically thick accretion disk) depends on the current accretion rate exhibit a change of the break frequency in the variability power spectrum during bursts of activity, i.e., in periods of a significant increase in the accretion rate. The dependence of the break frequency on the object’s X-ray luminosity (accretion rate) agrees well with the theory of a dipole neutron star magnetosphere compressed by a Keplerian accretion disk.

If a similar situation with a change in the accretion flow geometry occurs in accreting white dwarfs, then one might expect a similar change in the properties of their aperiodic variability. However, the number of white dwarfs with a significant magnetic field (i.e., with a field that is capable of destroying the accretion disk at great distances from the white dwarf surface) exhibiting bursts of the accretion rate is very small, the bursts are rare and irregular, and, consequently, it is very difficult to observe such systems in the low and high states. Such periods of an increase in the instantaneous accretion rate are much more often observed for systems with a weak magnetic field. As the object most suitable for testing this prediction, we chose the binary system SS Cyg—a well known dwarf nova, i.e., a binary system in which the periods of a low accretion rate onto the compact object are replaced by outbursts, the periods of active accretion (see, e.g., the review by Oskin 1996). It follows from the existing model of accretion disks around white dwarfs (see, e.g., King 1997; Lasota 2001) that, despite the absence of a significant magnetic field on the white dwarf in the low state, the optically thick accretion disk in this binary system still ends at a considerable distance from the white dwarf (> 5–10RWD), but not through the interaction with the stellar magnetosphere but through its evaporation and transformation into an optically thin flow (Meyer and Meyer-Hofmeister 1994; Liu et al. 1997; Meyer-Hofmeister and Meyer 2001). In the periods of peak bolometric luminosity, when the current accretion rate onto the white dwarf increases considerably, the optically thick accretion disk comes close to the white dwarf.

Since the X-ray flux from this system is fairly low (several mCrab, i.e., only a few photons per second per 1000 cm), it is very difficult to obtain a high quality power spectrum in the required frequency range (up to 1–5 Hz) from X-ray light curves. To measure the properties of the object’s aperiodic variability, we used its optical observations. Although the optically emitting regions are considerably larger in size than the X-ray-emitting ones, their sizes nevertheless do not exceed ~ 10¹⁰ cm and, hence, the smoothing of the variability due to the finite time it takes for light to traverse the emitting region plays no major role up to frequencies of the order of several Hz. It is in this frequency range that we carried out the studies presented here.

OPTICAL OBSERVATIONS

Influence of the Atmosphere on Photometric Measurements

The flux variations in the photometric series obtained with ground-based telescopes are determined by a number of factors. First of all, these include the object’s Poissonian photon counting noise. However, the influence of this noise on the power spectrum of the source’s flux variability is fairly easy to take into account by subtracting the constant level (P(f) ∝ const) produced by this noise from it.
In the case of the CCD array used in our measurements (EM CCD), additional noise of the photometric signal is produced by the electronic amplification cascade in the reception channel. This is because the signal amplification itself in the CCD array becomes noisy due to the Poissonian variations of the amplification cascade electrons (multiplicative noise). However, this amplification is a random variable whose values are uncorrelated in neighbouring exposures. Therefore, it actually leads to a slightly changed value of the constant level in the derived power spectra. The most significant factor that makes it difficult to measure the aperiodic variability parameters for sources is the influence of turbulence in the atmosphere. Because of this turbulence, chaotic variations of the refractive index always exist in the atmosphere. This, in turn, leads to changes in the shape of the stellar image at the telescope’s focus, their jitter, and scintillations.

To give an idea of what additional variability is produced by the atmosphere above the RTT-150 telescope, we present the variability power spectrum for a nonvariable star taken on September 2, 2010, in Fig. 1. Unfortunately, the properties of the atmosphere producing this additional (with respect to the Poissonian one) noise is not strictly fixed during the night, i.e., a correction for the atmosphere can be made by analysing the variability power spectrum for the reference star photographed at a slightly different time than that for the source being investigated only with a low accuracy.

Differential photometry is a popular method for combating the influence of these factors. In this method, the flux from the star being investigated is measured not directly but in comparison with one or more nonvariable field stars. Using the ratio of the fluxes from the investigated and (nearby) reference stars allows the influence of the changing atmosphere to be taken into account, at least to a first approximation (see, e.g., the power spectra of the photometric series obtained with the same RTT-150 telescope [Burenin et al., 2011]). However, a necessary condition for this method to be efficient is the requirement that the field stars be at least brighter than the investigated star. Otherwise, the statistical uncertainty in measuring the brightness of the investigated star will be determined not by the star itself but by the noise of the comparison star.

The optical brightness of SS Cyg in the low state is about 12 magnitudes. This allows USNO B.1 1335–0436095 at a distance of 2.06 arcmin from SS Cyg with a brightness $R \sim 11$ to be used as a reference star. However, during outbursts (i.e., in the periods of a high accretion rate in the binary system), the system’s brightness increases to $R \sim 8.5$, which makes the use of USNO B.1 1335-0436095 as a reference star nonoptimal. In this case, the star BD+42 4190 was used as a reference star nonoptimal. In this case, the star BD+42 4190 should be used. Here, we used both the first and second reference stars for the application of differential photometry.

### Table 1. Observations of SS Cyg on telescope RTT150 in 2010-2011, used in our work

| Date       | MJD(start) | Filter | Exp. ksec | dt msec |
|------------|------------|--------|-----------|---------|
| Aug. 24, 2010 | 55432.8.117 | g      | 12.3      | 11.7    |
| Aug. 31, 2010 | 55439.8.032 | g      | 24.9      | 8.1     |
| Sept. 2, 2010 | 55441.7.644 | g      | 28.5      | 8.1     |
| Sept. 3, 2010 | 55442.8.284 | r      | 7.9       | 8.1     |
| Sept. 3, 2010 | 55443.1.243 | g      | 7.3       | 8.1     |
| July 11, 2011 | 55753.8.617 | g      | 11.0      | 62.5    |

### RTT-150 Observations

The observations of SS Cyg during its outburst were performed with the Russian-Turkish 1.5-m telescope RTT-150 using a CCD photometer mounted at the Cassegrain focus $f = 1/7.7$. A log of observations is presented in Table 1. The photometric measurements were made with the ANDOR iXon DU-888 CCD array. The iXon DU-888 back-illuminated CCD approximately 4x4 arcmin in size is divided into 1024x1024 pixels. The CCD is equipped with electronic multiplication (EMCCD), which allows one to reduce considerably the readout noise effect at very short exposure times and, consequently, to use it for measuring the brightness of faint objects. The CCDs are cooled electronically to a temperature of -60°C. The entire field with the readout of all CCD pixels (1024x1024) can be imaged eight times per second; when reducing the readout region and binning the readout rows, the exposure time can be reduced to ~1-3 ms.

In our case, we used two approaches:

- When using USNO B.1 1335-0436095 at a distance of 2.06 arcmin from SS Cyg as a reference star, we recorded the image of the sky around SS Cyg with a width of about 14 arcsec (see Fig. 2) summed in the vertical direction into a one-dimensional strip. This allowed us to obtain images with a frequency of 123.46 Hz; the length of one exposure in our observations is 1.36 ms. The photometric measurements were made in a one-dimensional strip with a fixed center and the aperture width determined from the summed (over the interval of observations) one-dimensional brightness profile on the CCD. The CCD background illumination outside bright sources was approximated by a linear function at distances up to 100 pixels from the sources. As the aperture width, we took a value that was a factor of 8 larger than the full width at half maximum of the stellar profile. In our case, the choice of such aperture (with a fixed value of a wide aperture) stellar photometry is related primarily to the fact...
that we needed to gather the stellar flux as completely as possible to reduce the parasitic noise level of the atmosphere. Reducing the aperture width or using the aperture width determined for each specific frame, despite the fact that the shape of the stellar image on the detector changes in a chaotic way unknown to us—the image centroid moves over the detector, the fraction of the flux in the wings of the stellar image changes under the atmospheric effect, will cause the stellar flux variability amplitude to increase through atmospheric jitter.

- In 2010, we also used the method described above during our observations of SS Cyg in the high state, which is nonoptimal from the standpoint of maximizing the signal-to-noise ratio for the source due to the comparative faintness of the reference star. To maximize the signal-to-noise ratio in our photometric measurements of SS Cyg in the July 2011 observation of the high state, we changed the method and used BD+42 4190 as a reference star. Since the CCD size is about 4 arcmin, in this case, we cannot use the technique described above. In this case, we placed the reference star and the investigated source SS Cyg along the CCD diagonal and read out the entire CCD field by binning its pixels in 2x2 (see Fig. 3). In such a case, the time resolution was 62.5 ms. The photometric measurements were made with a fixed (circular) aperture. The count measurements in adjacent circles were used as the CCD background illumination measurements.

Fig. 1. Power spectrum of the flux variations for a bright nonvariable star in the series of RTT-150 observations early in September 2010 from ANDOR/iXon measurements. We see that the variability power spectrum flattens out at frequencies higher than several tens of Hz, approaching its “Poissonian” value (the estimated Poissonian noise level is indicated by the dotted line), i.e., the noise at these frequencies is produced predominantly by the Poissonian count rate of photons (and electrons in the amplification circuit of the ANDOR/iXon CCD array). The component in the frequency range 0.5–5 Hz arises from atmospheric scintillations and jitter.

Fig. 2. Region of the sky around SS Cyg observed with the high-speed ANDOR iXon DU-888 CCD during its high state. The comparison star (USNO B1 1335–0436095, mR = 11.0) is located in the left part of the image; SS Cyg is located in its right part. The image with the original CCD resolution is shown at the top; the one-dimensional profile obtained by the image addition along the vertical axis is shown at the bottom. The scale of the plot along the Y axis indicates the number of counts recorded at the points of the one-dimensional profile in 100 s. We see that the brightness of the reference star is several times lower than that of the investigated one.
RESULTS

The Low State

First of all, we checked whether the variability power spectrum for SS Cyg in quiescence was consistent with the predictions of the model of propagating fluctuations in an accretion disk with an inner boundary, i.e., whether there was a break in the power spectrum similar to that observed in accreting systems with disks truncated by the magnetospheres of compact objects (Revnivtsev et al. 2009, 2010). For this purpose, we used both RTT-150 data (see the table) and moderate-time-resolution (about 10–30 s) observations with telescopes at the Crimean Astrophysical Observatory (CrAO) (see Voloshina et al. 2009).

The power spectrum of the optical flux variability for SS Cyg obtained in these observations is presented in Fig. 4. Since the source’s flux variability is undetectable at high frequencies, Fig. 4 does not show the frequency range above \( \sim 0.1 \) Hz. We clearly see that the variability power spectrum has two characteristic regions – the region where the variability power behaves approximately as \( P \propto f^{-1} \) (the flat part in Fig. 4) and the region where the variability decreases with frequency as \( P \propto f^{-2} \), similar to what we observed for intermediate polars (see Revnivtsev et al. 2010). Note that a similar change in the pattern of behavior of the power spectra for accreting nonmagnetic white dwarfs was demonstrated previously by Kraicheva et al. (1999) and Pandel et al. (2003).

If we fit the power spectrum for SS Cyg by the analytical model \( f \times P(f) \propto [1 + (f/f_0)^4]^{-0.25} \) used in Revnivtsev et al. (2009), then the break frequency will be \((2.1 \pm 0.5) \times 10^{-3} \) Hz. For a white dwarf with a mass of 0.81\( M_\odot \) (Büker et al. 2007), this corresponds to the Keplerian rotation frequency of the matter at a distance of \((8.5 \pm 1.4) \times 10^9 \) cm. The inner disk radius estimated from the break frequency in the power spectrum agrees satisfactorily with the estimates based on other physical effects. In particular, the inner radius of the optically thick disk in the intermediate polar EX Hya estimated from the break frequency in the power spectrum of its flux variability, \(1.9 \times 10^9 \) cm (Revnivtsev et al. 2011), agrees, to within about 30%, with the results of the measurements made by analyzing emission line profiles, \( \sim 1–2 \times 10^9 \) cm (Hellier et al. 1987), and analyzing eclipses at different phases of the white dwarf pulsations, \( \sim 1.5 \times 10^9 \) cm (Siegel et al. 1989).

Interestingly, the inner boundary of the optically thick disk determined in this way from the source’s variability power spectrum agrees qualitatively with the predictions of the model of evaporating accretion disks around nonmagnetic white dwarfs (see, e.g., Liu et al. 1997).

The High State

In the high state of SS Cyg, we made its photometric observations in two outbursts. We managed to obtain photometric measurements at the very peak of the system’s optical brightness in the September 2010 outburst (see Fig. 5a) and at the optical brightness decline in the July 2011 outburst (see Fig. 5b).

In the September 2010 outburst, we made our measurements using USNO B.1 1335-0436095 as a reference star. As a result, the signal-to-noise ratio of the photometric series obtained by the method of differential photometry is much lower than the best one (the brightness of the ref-
ence star was lower than that of SS Cyg by a factor of 60-70). For this reason, the photometric series is essentially insensitive to the possible residual atmospheric jitter effects on the variability. Consequently, the power spectrum of the signal from SS Cyg at frequencies above approximately 0.5-1 Hz reaches a constant that represents the statistical measurement errors (see also the power spectra of nonvariable stars obtained by the method of differential photometry with RTT 150 by Burenin et al. 2011).

During the July 2011 outburst, we used the brighter star BD+42 4190. This allowed us (1) to obtain a higher-quality variability power spectrum for the objects and (2) to detect the residual atmospheric jitter effects.

Figure 6 presents the power spectrum for SS Cyg in the July 11, 2011 observation obtained by the method of differential photometry. We clearly see the residual variability of the recorded flux from the source due to an incomplete allowance for the atmospheric jitter and scintillation effects at frequencies above $\sim 0.05$ Hz (cf. the power spectrum for a nonvariable star in Fig. 1).

Changes of the Inner Disk Boundary

The pattern of change in the aperiodic flux variability of SS Cyg is clearly seen from Fig. 7. As the brightness (accretion rate) of the source rose, the fraction of the fast variability clearly increased at frequencies up to 0.01 Hz in the July 11, 2011 observation (i.e., during the source’s intermediate brightness) and up to 0.1 Hz in the observations early in September 2010 (i.e., during the source’s peak optical brightness).

It is in this frequency range that we should expect the appearance of an additional noise component due to the
Fig. 7. Power spectra of the optical flux variability for SS Cyg in periods with different accretion rates in the low state (a), in the period of an intermediate accretion rate (the July 11, 2011 observation) (b), and in the period of peak accretion rate (the September 2, 2010 observation) (c). The dashed curve indicates the model used to describe the power spectrum in the low state (see Fig. 4). The dotted curve indicates a similar model in which 0.091 Hz was substituted as the break frequency; this corresponds to the Keplerian rotation frequency of matter in a circular orbit near the surface of a white dwarf with mass $M = 0.81 M_\odot$ (the white dwarf radius was calculated using a formula from Nauenberg (1972)).

Thus, we may conclude that the results of our observations show that the accretion flow around a nonmagnetic white dwarf (in our case, the white dwarf in the binary system SS Cyg) is clearly divided into two regions the location of the boundary between which depends on the current accretion rate in the inner part of the accretion flow (where the main energy release takes place). In the model of an evaporating accretion disk (Meyer and Meyer-Hofmeister [1994]), this boundary separates the regions of optically thick and optically thin flows.

Interestingly, a distinct feature like a quasiperiodic oscillation (QPO) with a low Q ($Q = f / \Delta f \sim 1$) is observed near the break in the variability power spectrum for SS Cyg. The appearance of QPO near the break in the variability power spectrum is not unique to the object considered but is a rather common phenomenon in systems in which matter is accreted through two regions with different physical properties. For example, in magnetized neutron stars, in which matter from the optically thick disk penetrates into the magnetosphere (see, e.g., Revnivtsev et al. [2009]), in accreting black holes in a hard spectral state, in which matter from the optically thick disk transforms into an optically thin coronal flow (Wijnands & van der Klis [1999]). However, in the mentioned cases, the QPO Q factor is, as a rule, higher. It can be assumed that the appearance of QPO in the case of SS Cyg is associated with instabilities when matter penetrates from the optically thick accretion disk into the coronal flow.

The detection of a break in the variability power spectrum for nonmagnetic white dwarfs opens up possibilities for an independent estimation of their masses. Indeed, the inner radius of the accretion disk, which must exceed the white dwarf radius, can be estimated by measuring the break frequency in the object’s variability power spectrum at the peak of its optical-ultraviolet brightness. Next, given the equation of state for the white dwarf (i.e., its mass–radius relation), we can estimate its mass. Unfortunately, in our case, the statistical quality of the observational data at the peak accretion rate onto the white dwarf (September 2010) is too low to independently estimate the white dwarf mass by this method. New, higher-quality observations are needed for this purpose.

CONCLUSIONS

We analysed the pattern of aperiodic optical flux variability for the accreting nonmagnetic white dwarf SS Cyg. This work is a pilot project whose goal is to test the hypothesis that the accretion disk around the nonmagnetic white dwarf in SS Cyg is truncated at a certain distance from the white dwarf in the low state and approaches the white dwarf in the high state. For this purpose, we carried out special
observations of the source in the low and high states with a record (for CCD photometers) time resolution up to 123 Hz. We showed the following.

- In the low state, the power spectrum of the optical flux variability for SS Cyg is similar to the variability power spectrum for intermediate polar stars with a break in the range of frequencies $\sim 2 \times 10^{-3}$ Hz. This suggests that the optically thick accretion disk in SS Cyg is truncated/evaporated (Meyer and Meyer-Hofmeister 1994; Liu et al. 1997) at a distance of about $(8.5 \pm 1.4) \times 10^{9}$ cm, or $R \sim 10 R_{WD}$.

- In the high state, the flux variability amplitude for SS Cyg in the frequency range $10^{-3} - 1$ Hz is lower than that in the low one, 1.3%. However, it contains a much larger fraction of fast variability, up to frequencies of $\sim 0.1$ Hz that roughly correspond to the rotation frequency of matter in a Keplerian orbit near the white dwarf surface. In the state with the source’s maximum optical brightness, the break frequency is maximal, about 0.1 Hz; in the state with an intermediate brightness, the break frequency is about 0.01 Hz.

To further study the behaviour of the inner boundary of the optically thick accretion disk at various stages of the burst of the accretion rate, we need to carry out additional observations with a bright reference star in the instrument’s field of view and to try to compare more quantitatively the inner boundary of the accretion disk for nonmagnetic white dwarfs with the predictions of various theoretical models.

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