Observational evidence for matter propagation in accretion flows

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ABSTRACT

We study simultaneous X-ray and optical observations of three intermediate polars, EX Hya, V1223 Sgr and TV Col, with the aim of understanding the propagation of matter in their accretion flows. We show that in all cases the power spectra of the flux variability of binary systems in X-ray and optical bands are similar to each other, and the majority of X-ray and optical fluxes are correlated with time lag \(<1\) s. These findings support the idea that the optical emission of accretion discs in these binary systems largely originates as the reprocessing of the X-ray luminosity of their white dwarfs. In the best obtained data set of EX Hya we see that the optical light curve unambiguously contains some component that leads the X-ray emission by \(\sim 7\) s. We interpret this in the framework of the model of propagating fluctuations and thus deduce the time of travel of matter from the innermost part of the truncated accretion disc to the white dwarf surface. This value agrees very well with the time expected for matter threaded on to the magnetosphere of the white dwarf to fall to its surface. The data sets of V1223 Sgr and TV Col in general confirm these findings, but have poorer quality.

Key words: accretion, accretion discs – instabilities – binaries: general – white dwarfs – X-rays: binaries.

1 INTRODUCTION

Accretion is the main source of energy for a wide variety of astrophysical objects, from pre-main-sequence stars through white dwarf, neutron star and black hole binaries up to supermassive black holes in the centres of galaxies. The matter in accretion discs in these systems gradually moves towards the compact object, extracts gravitational energy and produce broad-band emission spectra. In spite of a general understanding of the formation of emission in accretion discs (Shakura & Sunyaev 1973; Done, Gierliński & Kubota 2007) and temperature distributions over the disc (Horne 1985), the very fact that the matter travels outside-in is not an easy thing to verify, even though it is essential for the whole accretion process.

Virtually the only way to verify this movement of the matter in the accretion flow is to study the time variability of its emission for different parts of the flow (except for perhaps the radial velocity component of the emission lines). Indeed, matter travels from the outer parts of the accretion flow towards the central compact object and thus any time variations of the mass transfer rate in the flow should be transported inwards (though with possible smearing due to the influence of viscosity).

This idea, together with the assumption that all accretion flow radii generate their own additional noise at characteristic frequencies corresponding to their dynamical times, is the essence of the model of propagating fluctuations (Lyubarskii 1997; Churazov, Gilfanov & Revnivtsev 2001; Kotov, Churazov & Gilfanov 2001; Uttley & McHardy 2001; Arévalo & Uttley 2006; Revnivtsev et al. 2009, 2010). The shortest time-scales in this model are introduced at the smallest radii, while the largest time-scales are introduced in the outer parts of the accretion discs. The inner parts of the disc add their noise to the mass accretion rate coming from the outer parts in a multiplicative way, thus naturally producing the observed linear relation between the amplitude of the fluctuations and the time-averaged flux (Lytuji & Oknyanskii 1987; Uttley & McHardy 2001) and log-normal distribution of instantaneous values of fluxes (Uttley, McHardy & Vaughan 2005; Revnivtsev 2008). The model implies that there should be a definite time lag between variabilities of emission in the outer and inner parts of the accretion flow. Note that here we can compare only variabilities at long time-scales, because short time-scale fluctuations are absent in the outer parts of the disc.

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This prediction is not easy to check owing to different complications. For example, in the case of galactic neutron star and black holes binaries it is relatively easy to observe the variability of the mass accretion rate in the innermost parts of the flow – in the X-ray energy band. At the same time, the mass accretion-rate variations in the outer parts of the accretion disc are almost invisible to us because the internal energy release of accreting matter at these radii is negligible in comparison with the energy absorbed by the disc from the illuminating X-ray flux (e.g. Dubus et al. 1999). Therefore, the optical emission of these systems is largely determined by the reprocessing of their X-ray luminosity (van Paradis & McClintock 1994) and thus does not provide us with information about internal mass accretion-rate variations at these radii. In accretion discs around supermassive black holes the characteristic time-scales can be as large as years and tens of years, therefore requiring large monitoring campaigns that are rarely available (see, however, Edelson et al. 1996; Desroches et al. 2006; Doroshenko et al. 2009; Arévalo et al. 2009).

One of the best available examples today of propagation of mass accretion-rate fluctuations (flickering) in accreting systems can be found among dwarf novae – accreting non-magnetized white dwarfs. In the work of Pandel, Córdova & Howell (2003) it was shown that the X-ray emission of accreting white dwarf VW Hya in quiescence is delayed with respect to its UV emission with $\Delta t \sim 100$ s. It is assumed that in this system the optically thick accretion disc, emitting UV radiation, ends at some distance from the white dwarf (WD) while the X-ray emission originates at the WD surface. The observed time lag was interpreted by authors as the time taken for the matter to travel from the inner parts of the optically thick accretion disc to the WD surface.

Due to the rather uncertain issue of disc truncation in the case of dwarf novae in quiescence, it is reasonable to look for better observational evidence of matter propagation in accretion flows. For this purpose we have selected luminous intermediate polars (IPs) – magnetized white dwarfs in which the accretion disc is truncated very close to the WD surface (although some IPs may be discless systems) but which, nevertheless, certainly have geometrically distinct regions generating the outgoing radiation. In intermediate polars, X-rays originate close to the surface of the WD, while the optical emission is mainly generated by the optically thick accretion disc or accretion curtains (Hellier et al. 1987; Patterson 1994; Hellier 1995). The optical emission of the disc can be powered either by its internal dissipation or by a reprocessing of the X-ray emission coming from the central object (Beuermann et al. 2004).

In the case of intermediate polars we have several advantages: (1) we know that the accretion disc is certainly truncated at some distance from the WD because we see X-ray pulsations and (2) we can make an estimate of the innermost radius of this accretion disc from the shape of the power spectra of the time variability (Revnivtsev et al. 2009, 2010). High mass accretion rates in these systems ensure that the white dwarf magnetosphere is not large and thus the internal energy release in the accretion disc is not completely negligible in comparison with the illuminating X-ray flux from the WD.

We have performed a set of simultaneous observations of EX Hya, V1223 Sgr and TV Col in X-ray and in optical spectral bands with the Rossi X-ray Timing Explorer (RXTE) Proportional Counter Array (PCA) and the 1.9-m telescope of the South African Astronomical Observatory. In this paper we present the results of this campaign.

2 OBSERVATIONS AND DATA REDUCTION

2.1 RXTE data

Our sample includes three of the brightest intermediate polars of the southern hemisphere (in order to ensure simultaneous observations with the South African Astronomical Observatory): EX Hya, V1223 Sgr and TV Col. These sources were observed by RXTE (Bradt, Rothschild & Swank 1993) for approximately 20 ks each in April 2010. A more detailed log of simultaneous RXTE–SAAO observations is presented in Table 1.

Data were analysed with tasks from the HEASOFT package, version V6.5. The RXTE/PCA background was estimated with the help of the model appropriate for faint sources, ‘CMFAINT_L7’. Light curves of sources were extracted from data of the first layer of PCU2 in the energy band 3–15 keV, maximizing the signal-to-noise ratio. All light curves were background-subtracted for the analysis.

2.2 SAAO data

For acquiring optical light curves we used the recently commissioned HIgh speed Photo-POlarimeter (HIPPO; Potter et al. 2010) on the 1.9-m telescope of the South African Astronomical Observatory during the nights beginning 2010 April 15, 17 and 18 (details of the observations are presented in Table 1). HIPPO is a two-channel instrument capable of simultaneous two-filtered photopolarimetry. None of the targets showed statistically significant polarization in any filter and consequently the photometry is reported here only. Data reduction proceeded as outlined in Potter et al. (2010) and data were binned to 1 s time resolution. Absolute timing was maintained via the observatory’s time service, which is phased by a GPS receiver.

3 POWER SPECTRA

Observations clearly show aperiodic variability of fluxes of all sources both in X-ray and optical spectral bands. Among the

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**Table 1.** Log of X-ray and optical observations used in the paper.

| Source  | Obs. ID     | RXTE Start time | Exp. (ks) | SAAO Start time (MJD) | Exp. (ks) | Filters |
|---------|-------------|-----------------|-----------|------------------------|-----------|---------|
| EX Hya  | 95305-02-01-00 | 55301.828       | 3.3       | 55301.818              | 5.1       | R, U    |
| EX Hya  | 95305-02-01-00 | 55303.986       | 3.2       | 55303.973              | 4.7       | R, U    |
| EX Hya  | 95305-02-02-02 | 55304.836       | 3.2       | 55304.822              | 4.6       | R, U    |
| V1223 Sgr | 95305-01-02-05(10) | 55305.066     | 2.7       | 55305.072              | 8.2       | R, U    |
| TV Col  | 95305-03-01-00 | 55301.752       | 2.0       | 55301.750              | 4.7       | I, B    |
| TV Col  | 95305-03-02-00 | 55303.764       | 3.4       | 55303.751              | 3.6       | R, U    |
| TV Col  | 95305-03-02-01 | 55304.744       | 4.6       | 55304.739              | 4.9       | R, U    |
obtained data sets, observations of EX Hya have the best quality (the source is brighter than TV Col in X-rays and the length of overlapping observations is much larger than for V1223 Sgr), therefore we will concentrate below on the case of EX Hya, while presenting similar results (if statistics allow us) for other sources.

An example of the light curves of EX Hya observed simultaneously with RXTE/PCA and SAAO is shown in Fig. 1. Close similarity between the curves is clearly seen.

The power spectra of variability of the source at these energies are very similar to each other (see Fig. 2). The shape of the power spectra can be adequately described by a simple analytical model describing the smooth break between the slope of the power spectrum at low frequencies \( P(f) \propto f^{-1} \) and at high frequencies \( P(f) \propto f^{-\gamma} \). Frequencies of the break in optical and X-ray data, collected in 2010 April, are \( f_{b,\text{opt}} = (1.5 \pm 0.1) \times 10^{-2} \) Hz and \( f_{b,\text{x}} = (1.7 \pm 0.3) \times 10^{-2} \) Hz, respectively. If we fit the power spectrum of variability of the X-ray flux of EX Hya, averaged over all observations in the RXTE archive (1996–2010, exposure time \( \approx 200 \) ks), we obtain the break frequency \( f_0 = (2.1 \pm 0.1) \times 10^{-2} \) Hz.

Assuming that the break frequency corresponds to the frequency of Keplerian rotation at the boundary of the magnetosphere, \( f_0 = \sqrt{GM_{\text{WD}}/R_{\text{in}}^3}/2\pi \) (see evidence for this statement in Revnivtsev et al. 2009), we can estimate the inner radius of the accretion disc in EX Hya. We adopt for the mass of the WD in EX Hya \( M_{\text{WD}} = 0.79 M_{\odot} \) (Beuermann & Reinsch 2008), and thus its radius (using Nauenberg 1972) is \( R_{\text{WD}} \approx 7 \times 10^8 \) cm. The estimate of the innermost radius of the disc from the value of the break frequency is \( R_{\text{in}} \approx 1.9 \times 10^7 \) cm, or \( \sim 2.7 R_{\text{WD}} \).

In fact, it is likely that the transition between the accretion disc and the WD magnetosphere is not a simple perfect circle and forms something like accretion curtains (Hellier et al. 1987; Hellier 1995). Therefore it would be reasonable to say that the position of the break in the power spectrum measures the position of these transition regions. It is remarkable to note that estimates of distance of these accretion curtains from the WD surface made from completely different physical arguments, i.e. \( R_{\text{in}} \sim 1–2 \times 10^6 \) cm from analysis of emission-line profiles (Hellier et al. 1987) and \( R_{\text{in}} \sim 1.5 \times 10^6 \) cm from analysis of spin-modulated eclipses of the emission region (Siegel et al. 1989), are very close to our estimates.

This value of the radius of the transition region (or size of the WD magnetosphere) tells us that it is truncated well below the corotation radius. Depending on the details of the coupling of the WD magnetosphere to the accretion disc, it might lead to a certain spin-up of the WD rotation. Note that the white dwarf in EX Hya is indeed spinning up (see the latest measurements in Mauche et al. 2009).

### 4 TIME LAGS

The similarity of optical and X-ray power-spectra variability of EX Hya is naturally predicted by the model of propagating fluctuations. Variations of the mass accretion rate, flowing through the inner part of the accretion disc (which creates optical/UV emission), result in a modulation in the mass accretion rate at the WD surface, thus generating variable X-ray flux. If the optical/UV light is powered mainly by internal dissipation in the disc, then X-ray emission variations should lag the optical variation by the matter travel time in the magnetosphere,

\[
\Delta t \sim \frac{R_{\text{in}} - R_{\text{WD}}}{\sqrt{GM_{\text{WD}}/R}} \sim 5 \text{ s}.
\]

More accurately, if we assume that the matter is accelerating from zero velocity at \( R_{\text{in}} \) towards the white dwarf and moves radially, then

\[
\Delta t = \sqrt{\frac{R_{\text{in}}}{2GM_{\text{WD}}}} \int_{R_{\text{in}}}^{R_{\text{WD}}} \frac{u^{1/2} \, du}{(1-u)^{3/2}},
\]

where

\[
u = \frac{R}{R_{\text{in}}}.
\]
The variable mass accretion rate with broad-band variability (created in the extended accretion disc) modulates the optical emission emerging from the innermost parts of the accretion disc at the boundary of the magnetosphere and then, after the matter travel time, modulates the X-ray flux from the WD surface. The X-ray flux, in turn, illuminates the inner part of the disc, which then creates optical variations in line with the variations of X-ray flux.

\[ \Delta t = \sqrt{\frac{R_{\text{wd}}^2}{2GM_{\text{wd}}}} \times \left[ \frac{\pi}{2} - \arcsin \left( \frac{R_{\text{wd}}}{R_{\text{wd}}^2 - R_{\text{wd}}^2/c^2} \right) + \frac{1}{2} \sin \left( 2 \arcsin \left( \frac{R_{\text{wd}}}{R_{\text{wd}}^2 - R_{\text{wd}}^2/c^2} \right) \right) \right], \]

which for our parameters is \( \sim 8 \) s. However, if the reprocessing of the X-ray emission plays a dominant role in heating of the accretion disc (note that surface of the WD is heated by X-rays anyway), then the optical emission will lag the X-rays by the light-crossing time \( \Delta t \sim (R_{\text{wd}} - R_{\text{WD}})/c \sim 6 \) ms. Generation of this variability pattern is schematically shown in Fig. 3.

In both cases the flux variability of the source in these spectral bands should be closely correlated. This is indeed observed. The curves are strongly correlated and the peak of the cross-correlation is \( \sim 0 \) (see Fig. 4). This directly shows that the variable optical emission of EX Hya is mainly powered by reprocessing of X-rays (the light-crossing time lag \( \sim 6 \) ms cannot be detected with the time resolution of our data sets).

However, it is seen on Fig. 4 that the cross-correlation obviously is not symmetric with respect to zero – there is much more correlation at negative delays (optical leads X-rays) than on positive. This indicates that we do see some part of the internal dissipation in the disc and its variability leads the X-rays.

In order to demonstrate this point we have simulated the X-ray and optical light curves and compared their cross-correlations with the observed one. We have simulated the X-ray light curve \( X(t) \), which is supposed to be representing mass accretion-rate variations on the WD surface, as a curve, the power spectrum of which has a shape measured by us (see above). Then we have simulated the optical curve \( O(t) \). This curve consists of two parts, one having zero time lag with respect to the X-ray curve (simple reprocessing of the illuminating X-ray flux) and another that precedes the X-ray curve due to the finite matter-travel time from the place of generation of the optical emission to the WD surface. Therefore, the curve \( O(t) \) was modelled as a sum of two copies of the simulated X-ray light curve with a range of time lags between them \( (\Delta t) \) and the fractional contribution of the delayed component given by \( A \): \( O(t) = (1 - A) X(t) + AX(t + \Delta t) \). The cross-correlation of the resulting curves was compared with that obtained from observations in the range of delays \( [-20, +20] \) s. The \( \chi^2 \) contour plot with different values of the time lag and fractional contributions of the delayed curve is shown in the upper panel of Fig. 5. The minimum of the formally calculated \( \chi^2 \) is approximately 20.5 for 39 degrees of freedom (41 data points and 2 parameters), but we should keep in mind that the neighbouring values of the cross-correlation are not statistically independent because they use almost the same samples of observed points on light curves, therefore the face values of \( \chi^2 \) cannot be used to calculate true statistical significances. If we try to rescale the obtained minimum of the \( \chi^2 \) value to the number of degrees of freedom (assuming that the fit is good), the formal 1σ confidence intervals on the parameters would be \( \Delta t = 7 \pm 1 \) s and \( A = 0.5 \pm 0.05 \). It is remarkable that the lag between X-ray and optical data agrees perfectly with the estimate of the matter travel time in the magnetosphere of EX Hya (see above).

5 V1223 SGR AND TV COL

The quality of the data sets for V1223 Sgr and TV Col is somewhat worse, therefore we cannot repeat in detail the analysis which we have done for EX Hya. However, we do see the same similarities between power spectra in the X-ray and optical bands and we do see significant correlation between them (Fig. 6).

We would like to mention some peculiarity in the power spectrum of variability of the X-ray flux of TV Col during our observations in 2010. The power clearly has some excess (quasi-periodic oscillation, hereafter QPO) at frequencies around \( f_{\text{QPO}} \sim 1.6 \times 10^{-2} \) Hz with an amplitude of 5 ± 1 per cent. On the power spectrum obtained from all data in the RXTE archive this excess is not so narrow, indicating that it might be either a transient phenomenon or a phenomenon with a floating centroid frequency. It is interesting to note that this QPO is located close to the frequency of the break in the power spectrum \( f_{\text{break}} \sim 5.1 \times 10^{-2} \) Hz in this case. Such
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(i) The power spectra of the flux variability of EX Hya in optical and X-ray spectral bands are very similar to each other and have a break in the slope $P(f) \propto f^{-1}$ to $P(f) \propto f^{-2}$ at the frequency $f_0 \sim 0.02$ Hz. Following Revnivtsev et al. (2009, 2010) we relate this break to the transition of the matter from disc flow at large distances from the WD to magnetospheric flow closer to the WD. The break in the power spectrum is at much higher frequencies than the WD spin frequency, thus indicating that the disc ends within the corotation radius.

(ii) X-ray and optical light curves are strongly correlated with the peak of the cross-correlation function around zero time lag. We interpret this as a sign of the reprocessing of X-ray light at the surface of the optically thick accretion disc, the accretion curtains and the WD.

(iii) However, we detect a clear and stable asymmetry of the X-ray-optical cross-correlation function, which indicates that at least some part of the optical variability leads the X-ray variability. We measure a time lag between these variabilities $\Delta t \sim 7$ s, which is consistent with the travel time of matter from the inner radius of the accretion disc (or accretion curtains) along the magnetosphere to the white dwarf surface. We interpret this as a clear sign of a propagating fluctuation in the accretion flow. In this particular case we estimate that approximately 50 per cent of the optical variability precedes the variability of the X-ray light curve, indicating a significant contribution of the internal energy dissipation in the disc to the total energy budget of the inner part of the optically thick accretion disc.

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