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Probing Disk Structure of Dwarf Novae and Cataclysmic Variables Using Broadband Noise

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Flicker noise and its variations in accreting systems have been a diagnostic tool in understanding the structure in accretion disks. I study the nature of time variability of brightness of non-magnetic cataclysmic variables. DN systems demonstrate band limited noise in the UV and X-ray energy bands, which can be adequately explained in the framework of the model of propagating fluctuations. The detected frequency breaks in the range (1-6) mHz indicates an optically thick disk truncation in the inner disk of some dwarf novae systems. Analysis of other available data (SS Cyg, SU UMa and WZ Sge) indicate that during the outburst the inner disk radius moves towards the white dwarf and receeds as the outburst declines to quiescence. Cross-correlations between the simultaneous UV and X-ray light curves show time lags in the X-rays of 96-181 sec consistent with the travel time of matter from a truncated inner optically thick disk to the white dwarf surface. All this suggests that DN and other plausible nonmagnetic systems may have optically thick disk truncation where accretion may occur through coronal/hot flows in the inner disk region. I compare magnetic and nonmagnetic systems in terms of their broadband noise characteristics and summarize findings in other types of nonmagnetic CVs which in general show compliance with the model of propagating fluctuations. Finally, I discuss comparisons with X-ray binaries.

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1. Introduction

Cataclysmic Variables (CVs) are a class of X-ray binaries transfering mass from a donar star to a compact star which is a white dwarf. They constitute a laboratory for accretion physics, and disk theory together with dynamics of outflows and interaction with surrounding medium. CVs can be studied in two main classes. An accretion disk forms in cases where the magnetic field of the WD is weak or nonexistent ($B < 0.01$ MG), such systems are referred as nonmagnetic CVs characterized by their eruptive behavior (see Warner 1995, Balman 2012). The other class is the magnetic CVs (MCVs) divided into two sub-classes according to the degree of synchronization of the binary. Polars have strong magnetic fields (230 MG>B>20 MG) which cause the accretion flow to directly channel onto the magnetic pole/s of the WD inhibiting the formation of an accretion disk and causing the WD rotation to synchronize with the binary orbit. The second class of MCVs are the Intermediate Polars which have less field strength (1-20 MG) and are thus asynchronous systems (see Warner 1995, Mouchet et al. 2012 for a review on MCVs).

The material in the inner disk of nonmagnetic Cataclysmic Variables (CVs) initially moving with Keplerian velocity dissipates its kinetic energy in order to accrete onto the slowly rotating WD creating a boundary layer (BL) (see Warner 1995, Kuulkers et al. 2006). Standard accretion disk theory predicts half of the accretion luminosity to originate from the disk in the optical and ultraviolet (UV) wavelengths and the other half to emerge from the boundary layer as X-ray and/or extreme UV (EUV)/soft X-ray emission which may be summarized as $L_{BL}\sim L_{disk}=GM_{WD}\dot{M}_{acc}/2R_{WD}=L_{acc}/2$ (Lynden-Bell & Pringle 1974, Godon et al. 1995, Suleimanov et al. 2014). During low-mass accretion rates it is expected that, $\dot{M}_{acc}<10^{-(9-9.5)}M_{\odot}$, the boundary layer is optically thin (Narayan & Popham 1993, Popham 1999) emitting mostly in the hard X-rays (kT$\sim10^{(7.5-8.5)}$ K). For higher accretion rates , $\dot{M}_{acc}\geq10^{-(9-9.5)}M_{\odot}$, the boundary layer is expected to be optically thick (Popham & Narayan 1995) emitting in the soft X-rays or EUV (kT$\sim10^{(5-5.6)}$ K). The transition between an optically thin and an optically thick boundary layer, also depends on the mass of the white dwarf (also rotation) and on the alpha viscosity parameter and the optical depth of the flow.

Dwarf novae (DNe) are a class of nonmagnetic CVs where matter transfered by means of an accretion disk at a low rate (quiescence) is interrupted every few weeks to months or sometimes with longer durations by intense accretion (outburst) of days to weeks where $\dot{M}$ increases to a high state (Mauche 2004 and references therein). The nonmagnetic nova-likes (NLs) are found mostly in a state of high mass accretion rate with a few $\times10^{-8}M_{\odot}$ yr^{-1} to a few $\times10^{-9}M_{\odot}$ yr^{-1} and have winds that are about or less than 1% of the source accretion rate, with velocities 200-5000 km/s (see Balman et al. 2014 and references therein).

2. The Broadband noise and relevance to disk structure

Conventional flickering studies of CVs have been conducted using eclipse mapping techniques. Some of these studies in quiescent dwarf novae indicate that mass accretion rate diminishes by a factor of 10-100 and sometimes by 1000 in the inner regions of the accretion disks as revealed by the brightness temperature calculations which do not find the expected $R^{-3/4}$ radial dependence of brightness temperature expected from standard steady-state disks (e.g., Z Cha, OY Car, V2051 OPh and V4140 Sgr: see Balman 2014 for a review). On the other hand, this flattening in the brightness temperature profiles may be lifted by introducing disk truncation in the quiescent state (e.g., r $\sim$ 0.15R$_{L1}$ $\sim$4$\times$10^9 cm; DW UMa, a nova-like: Biro 2000). A comprehensive UV modeling of accretion disks at high accretion rates in 33 CVs including several nova-likes and old novae (Puebla et al. 2007) indicate an extra component from an extended optically thin region (e.g., wind, corona/chromosphere) evident from the strong emission lines and the P Cygni profiles. This study also indicates that the mass accretion rate may be decreasing 1-3 orders of magnitude in the inner disk region.

Another diagnostic tool proposed to study the inner disk structure in accreting objects is the aperiodic variability of brightness (broadband noise) of sources in the X-rays. While the long timescale variability might be created in the outer parts of the accretion disk (Warner & Nather 1971), the relatively fast time variability (at f >few mHz) originates in the inner parts of the accretion flow (Bruch 2000; Baptista & Borteletto 2004). Properties of this noise is similar to that of the X-ray binaries with neutron stars and black holes. Now, the widely accepted model of origin for this aperiodic flicker noise is a model of propagating fluctuations (Lyubarskii 1997, Revnivtsev et al. 2009,2010, Uttley et al. 2011). The modulations of the light are created by variations in the instantaneous value of the mass accretion rate in the region of the energy release. These variations in the mass accretion rate, in turn, are inserted into the flow at all Keplerian radii of the accretion disk due to the stochastic nature of its viscosity and then transferred toward the compact object. Thus, variations are on dynamical timescales. This model predicts that the truncated accretion disk should lack some part of its variability at high Fourier frequencies.

The truncation of the optically thick accretion disk in DNe in quiescence was invoked as a possible explanation for the time lags between the optical and UV fluxes in the rise phase of the outbursts (Meyer & Meyer-Hofmeister 1994, Stehle & King 1999), and for some implications of the DIM (see Lasota 2004) or due to the unusual shape of the optical spectra or light curves of nonmagnetic CVs (Linell et al. 2005, Kuulkers et al. 2011).

2.1 The Dwarf Nova case: SS Cyg and others

A recent work by Balman & Revnivtsev (2012) have used the broad-band noise characteristic of selected DN in quiescence (only one in outburst: SS Cyg) and studied the inner disk structure and disk truncation via propagating fluctuations model. The power spectral densities (PDS) expressed were calculated in terms of the fractional rms amplitude squared following from (Miyamoto et al. 1991). The light curves were divided into segments using 1-5 sec binning in time and several PDS were averaged to create a final PDS for sources while the white noise levels were subtracted resulting in the rms fractional variability of the time series in units of $(\mathrm{rms/mean})^2$/Hz. This was multiplied with the frequencies to yield νP_ν versus ν. The broad-band noise structure of the Keplerian disks often show $\propto f^{-1...-1.3}$ dependence on frequency (Churazov et al. 2001, Gilfanov et al. 2005), and this noise will show a break if the optically thick disk truncates as the Keplerian motion subsides. Balman & Revnivtsev (2012) show that for five DN systems, SS Cyg, VW Hyi, RU Peg, WW Cet and T leo, the UV and X-ray power spectra show breaks in the variability with break frequencies in a range 1-6 mHz, indicating inner disk truncation in these systems. The truncation radii for DN are calculated in a range $\sim$(3-10)$\times$10^9 cm including errors (see Table 2 in Balman & Revnivtsev 2012). Balman (2014) presents preliminary PDS analysis of three more DNe with relevant break frequencies.

The same authors used the archival *RXTE* data of SS Cyg in quiescence and outburst and show that the disk moves towards the white dwarf during the optical peak to $\sim 1\times10^9$ cm ($\sim$50 mHz) and receeds as the outburst declines to quiescence to 5-6$\times10^9$ cm ($\sim$5 mHz). This is shown for a CV, observationally, for the first time in the X-rays (see Figure 1 top left panel). The quiescence and outburst PDS of SS Cyg is also studied in Revnivtsev et al. (2012) and reveals very similar results to X-rays and no break during the optical peak out to a frequency of 0.1 Hz.

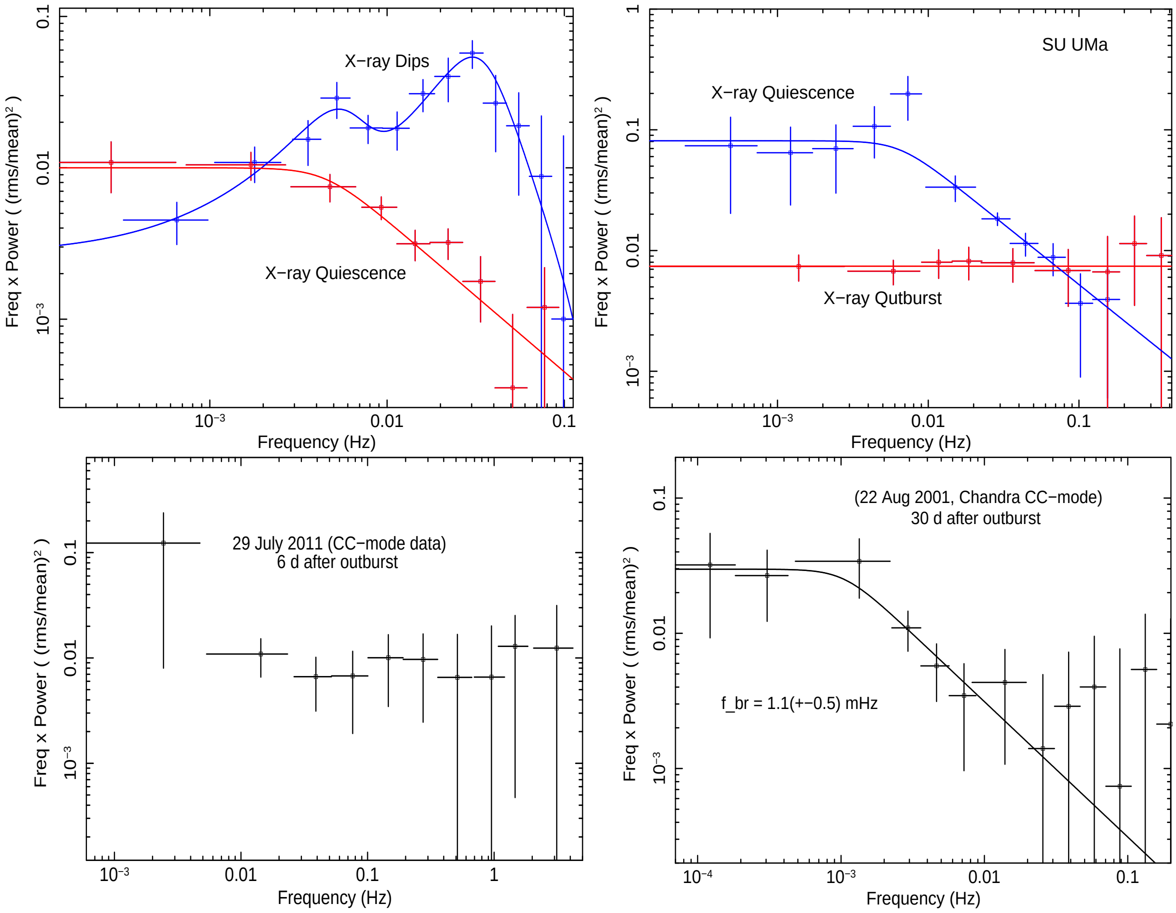

Figure 1: Broadband noise characteristics of different dwarf novae in quiecence and outburst. The top left is the PDS of SS Cyg in quiescence (red) and optical peak of the outburst (blue) noted as X-ray dips. The top right is the PDS of SU UMa using six consecutive outbursts. The quiescent PDS is in blue and the PDS in the peak of the outburst is in red color. The bottom left is the PDS of WZ Sge six days after the outburst during the peak of the outburst. The bottom right is the PDS of WZ Sge 30 days after the outburst in late decline.

An analysis on the *RXTE* data of SU UMa in quiescence and outburst following six consecutive outburts reveal a similar broadband noise structure to SS Cyg in quiescence showing a break frequency $\sim$ 5.5-7.5 mHz with a truncated optically thick disk $\sim 3.8\times10^9$ cm. The preliminary analysis of the outburst data during the X-ray suppression episodes (optical peak of the outburst) indicates no disk truncation or a truncation around 0.1 Hz (see Figure 1 top right panel).

WZ Sge is a short period SU UMa type dwarf nova with long interoutburst interval of 20-30 yrs as opposed to the recurrence time of 12-19 d for SU UMa (Collins & Wheatley 2010). The most recent outburst of WZ Sge in July-August 2001 was observed using the *Chandra* Observatory (see Balman 2014 and references therein). I have performed a peliminary power spectral analysis of the four ACIS-S (Advanced Camera Imaging Spectrometer) observations obtained in the continuous-clocking (CC) mode, in the same manner with SS Cyg and SU UMa and derived similar averaged PDS during the peak of the optical outburst on 6, 15, 30, and 58 days after the optical discovery. The PDS of 6th day and 30th day after the optical detection is given in the lower panels of Figure 1. There seems to be no break (or a break around 0.1 Hz) in the left panel 6 days after the optical detection during the optical peak phases, but after the decline sets in about 30 days after the detection of the outburst, there is optically thick disk truncation with a break frequency at around $\sim$ 1.1 mHz translating to an approximate truncation around 1.3×10^{10} cm. Therefore, SU UMa and WZ Sge indicate a similar behaviour of the disk during the outburst to SS Cyg where the inner disk moves in towards the WD during the optical peak and moves out in decline to quiescent location further out. However, I note that there may be variations in the break frequency during quiescence as noticed in further PDS analysis of WZ Sge and other DNe.

Balman & Revnivtsev (2012), also calculated the cross-correlation between the simultaneous UV and X-ray light curves (obtained in quiescence) by subtracting the zero time lag components in the five DNe PDS, yielding time lags consistent with delays in the X-rays of 96-181 sec (see the paper on details of the modeling). The lags occur such that the UV variations lead X-ray variations as the accreting material travels onto the WD, the variations are carried from the UV into the X-ray emitting region. The long time lags of the order of minutes can be explained by the travel time of matter (viscous flow) from a truncated optically thick inner disk to the white dwarf surface. Zero time lags ($\sim$ light travel time) indicate irradiation effects in these systems since the authors do not have resolution better than 1 sec.

2.2 The inner Disk Structure in other CVs

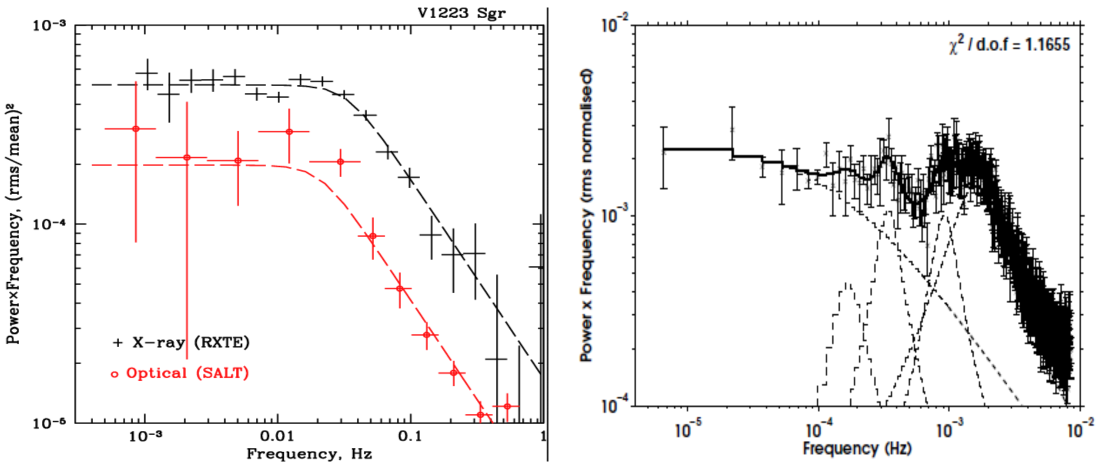

Figure 2: The broadband noise structure in other CVs. On the left is the PDS of an Intermediate polar type MCV obtained in the X-rays (RXTE) and optical (SALT) wavelengths (Revnivtsev et al. 2011). On the right panel is the PDS of the nova-like VY Scl system MV Lyr in the optical wavelengths (Kepler data: Scaringi et al. 2012).

Revnivtsev et al. (2010) study the power spectra of the variability of seven IPs containing magnetized asynchronous accreting WDs in the optical and three of them (EX Hya, V1223 Sgr, TV Col), both in the X-rays and the optical (see also Revnivtsev et al. 2011). Their time variability and broadband noise can be explained by the propagating fluctuations model in a truncated optically thick accretion disk in a similar fashion to DNe except that the truncation in IPs is caused by the accreting material being channeled to the magnetic poles of the WD and in DNe the physical conditions in the flow changes that reaches the WD at the end. Accretion-powered X-ray pulsars and asynchronous magnetic white dwarfs (intermediate polars) have magnetic fields strong enough to disrupt the inner parts of the accretion disks where the fastest variability timescales associated with the innermost regions of the disk should be absent or reduced in their power spectra. The authors' work show that the power spectra have breaks at Fourier frequencies associated with the Keplerian frequency of the disk at the white dwarf magnetospheric boundaries. The values of the break frequencies for V1223 Sgr in the optical and in X-rays are: $f_{\rm break,opt} = (2.1 \pm 0.5) \times 10^{-2}$ Hz, $f_{\rm break,X\text{-}ray} = (3.36 \pm 0.3) \times 10^{-2}$ Hz (in order to determine the $f_{\rm break}$ values χ^2 minimization have been used with similar fiting function to DNe). The break frequencies are compatible at the 2σ level for the optical and the X-rays and yield disk truncation at around $r_m \sim 1.6 \times 10^9$ cm or 2.8 $R_{\rm WD}$ (see Figure 2 for the PDS). This truncation radius is around $r_m \sim 2 \times 10^9$ cm for EX Hya.

Revnivtsev et al. (2011) show that in three cases the PDS of flux variability 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. Thus, the variable component of the optical emission from the accretion disks in these binary systems originate from a component that is due to the reprocessing of the X-ray luminosity in these systems. In the EX Hya data, they detect that optical emission leads the X-ray emission by about 7 s. The authors interpret this in the framework of the model of propagating fluctuations consistent with the travel time of matter from the truncated accretion disc to the white dwarf surface. The X-ray/UV time lags observed by Balman & Revnivtsev (2012) in the case of DN systems compared with those, detected for a magnetic Intermediate Polar allows us to make a rough estimate of the viscosity parameter $\alpha \sim 0.1$-0.3 in the innermost parts of the accretion flow of DN systems.

Some optical band studies using *Kepler* data (Scaringi et al. 2012) for the nova-like CV MV Lyr reveals that the source has log-normal flux distribution in the rms-flux relation and the origin of variablity is the multiplicative processes travelling from the outer to inner disc (as opposed to simple additive processes) proposed by the propogating fluctuations model mentioned in section[2]. The long term *Kepler* analysis of MV Lyr shows that all PSDs indicate single or several quasi-periodic oscillations (QPOs) along with a frequency break (see Figure 2 right panel). The PDSs show variations (at different times) and different QPOs in the long term observation of MV Lyr in the high state of the source (note that the low frequency break remains similar). This frequency break, at about 1-2 mHz, may be similar in origin to the the breaks observed in DNe in quiescence. Scaringi et al. (2013) calculates simultaneous optical lightcurves in differents bands, and find soft lags of 3-10 sec where the blue photons are observed before the red ones, at the lowest observed frequencies, with larger lags at low frequencies. This may be related to the reprocessing of harder radiation in the UV and X-ray regimes by the outer cooler disk on possibly thermal timescale. This may be similar to the peak at around zero lag in the cross-correlation analysis of UV and X-ray lightcurves of DNe and IPs (see Balman & Revnivtsev 2012, Revnivtsev et al. 2011).

3. Discussion and conclusions

DNe broadband noise characteristics in the X-rays indicate existence of frequency breaks (1-6 mHz) in quiescence as a result of truncation of the optically thick accretion disks detected in at least 8 systems in a range $\sim$(3.0-10.0)$\times 10^9$ cm. This can explain the UV and X-ray delays in the light curves during the outburst stage and indicate that the quiescent accretion in DNe may occur through optically thin hot flows (some mixture of thin-thick flow) in the inner disk. Time delays detected in a range of 96-181 sec, are also consistent with matter propogation timescales onto the WD in a truncated optically thick nonmagnetic CV disk in quiescence. Peaks near zero time lag in four systems indicate that part of the UV emission may arise from reprocessing of the X-ray emission. An α of 0.1-0.3 may be estimated for the inner regions of the DNe accretion disks in quiescence using comparative time lags between the X-ray and the UV or optical light curves of magnetic CVs and DNe. The PDS analysis of the X-ray data in the outburst stage of DNe indicate that the rms variability diminishes as expected since the optically thick disk is radiation supported in a high state with low variability and the disk reaches all the way or very close to the WD in three studied cases, SS Cyg, SU UMa, and WZ Sge during the optical peak of the outburst and the broadband noise reveals that the disk pulls out during the decline to a quiescent location.

Note that the DNe PDS is a power law in P_ν versus ν prescription with a frequency break in the quiescent stages. Eight systems were sucessfully modeled with a power law index α=1 where after the break in the frequency α=2 in quiescence. In the outburst, the systems show α=1 component out to around 0.1 Hz after which there no noise detected. However, a flat-topped BLN is detected in SS Cyg that extends to slightly higher frequencies. I underline that the number of observed sources and analysis is scarce to yield definitive conclusions about the entire DNe class.

In general, DNe broadband noise in quiescence and outburst show similarities to XRBs. The scenario of the accretion flow around a WD in quiescence and outburst, might resemble to that of the black hole (BH)/neutron star (NS) accretors with an optically thick colder outer accretion disk and an optically thin hot flow in the inner regions where the truncation occurs (see review by Done et al. 2007). The appearance of a hot flow (e.g., ADAF-like or a mixture of thick-thin flow) in the inner-most regions of the accretion disk will differ from that of ordinary rotating Keplerian disk because it is no longer fully supported by rotation, but might have a significant radial velocity component with sub-Keplerian speeds. Some broadband noise studies with high S/N optical data of a few nova-like or DNe indicate similar rms-flux relationship (log-normal flux distribution) derived for XRBs indicating that the propagating fluctuations model assumed in the X-ray broadband noise analysis is valid for CVs. These optical band studies also show low frequency disk QPOs in the optical and possible soft lags indicating reprocessed optical light in these systems consistent with X-ray results.

In the BH XRBs, which will have relevence to nonmagnetic CV systems, low hard states have flat-toped BLN with low frequency breaks around 0.01 Hz in P_ν versus ν prescription (see van der Klis 2006). They do not have the power law broadband noise structure depicted by the dominating optically thick disk variations. During the state changes in BH binaries the thermally dominant state or the high state has the most contribution from the disk with a power law continuum in the PDS between 0.1-10 Hz. The power law index of the PDS, α, is 0.7-1.2 with sometimes a break to an index about 1.5-2 at around 3 Hz (see review by van der Klis 2006). These charactristics resemble to the DNe in quiescence except that the BH variability is always at comparatively higher frequencies. The following very high state in BH state transitions (in transient outbursts) shows more noise in the high frequencies compared to the high states, but involves a strong band limited noise (flat-topped noise) in the PDS (as opposed to power law PDS) and some QPOs may be found depending on the spectral contributions. I note here that recent studies (see review by Belloni 2010) indicate that the high state and very high state may be broken into several stages/states and is more complex in nature begining from an intermediate hard state to the jet line (jet production), next a soft-intermediate state, and following high-soft state and corresponding anomalous states. A basic state change during the outburst from a high state to a very high state is detected in SS Cyg clearly (Balman & Revnivtsev 2012), but in relatively lower frequencies since the gravitational potential well around the BH is deeper than a WD. The other two DNe sources, also, show the diminishing power law variability towards the very high state, but they seem not to show the strong band limited flat-topped noise component. In both NS and BH binaries in state changes from low to intermediate states all components of the broadband noise increase in frequency become weaker and more coherent. This proceeding paper reveals the same may be occuring in at least the three cases of SS Cyg, SU UMa and WZ Sge. However, I note that a power law noise component (PDS in P_{ν} vs. ν) seems always present in DNe and plausibly nonmagnetic CV broadband noise across state changes.

The magnetic CVs (MCVs) disks show rather smaller optically thick disk truncation radii (0.9-2.0)$\times10^{9}$ cm as a result of channeling of the accretion flow to the magnetic poles of the WD. The values of the break frequencies in the PDS of IPs can be used to make estimates of the inner radii of the truncated accretion disks and the white dwarf magnetic fields. In all cases of studied IPs, the PDS in the X-ray and optical bands are similar to each other, and show correlation with time lag $<$1 s which indicates that part of optical emission may arise from reprocessed X-ray/UV emission from the polar caps. A 7 sec time lag detected for EX Hya between the optical and X-rays (X-rays lag) reveals matter propogation timescale from the inner disk to the magnetic poles which is not a light travel time effect. These results are analogous to NS XRBs with magnetic fields that yield disk truncation as in IPs. In general, Revnivtsev et al. (2009) show for accreting NS binaries the break in the PDS is the transition from the disk to the magnetospheric flow at the frequency characteristic of the accretion disk truncation radius (magnetospheric radius). They find that the PDS break frequency resembles to the spin frequency in corotating pulsars which strongly suggests that the typical variability timescale in accretion disks is close to the Keplerian frequency. Z sources which are NS XRBs have mostly powerlaw noise lower than ($<$) 1 Hz on the Flaring Branch whereas QPOs and BLN as in a flat-topped noise exits in other higher states of the Z sources (see van der Klis 2006). Atoll sources (other NS XRBs) show very low frequency noise that is a power law in similar frequency ranges $<$ 1 Hz in the upper banana state during high accretion rate of these systems. In lower banana and Island states of Atoll sources there is low frequency flat-topped BLN noise not a power law. Thus, Flaring branch Z sources and high state Atoll sources seems to have similar PDS to intermediate polars.

CONFERENCE DISCUSSION

DMITRY BISIKALO: What are the reasons of disk radial motion ?

SOLEN BALMAN: During the outburst the disk becomes optically thick moves in towards the WD as the accretion rate is increases like about two orders of magnitude. The alpha parameter in the flow also increases and the disk becomes hot. As the material is spead suddenly around the instability region outside towards the tidal radius and towards inside to the WD, the momentum flux also increases and the enchanced accretion flows inside (which then will fill out any truncated disk region given a time delay). Note that this truncated region need not be empty space but some optically thin-thick flow region which then will become optically thick during the enhanced mass transfer episodes.

JAMES BEALL: Is the flattening of the disk spectrum (in the eclipse maps) away from the Sakura-Sunyaev Disks related to opacity changes or clumping of the inner disk flow on to the compact object ?

SOLEN BALMAN: It is probably related to the opacity changes as the flow becomes optically thin or with thin-thick regions, ect. Clumping in CV disks is not something that is observed. At the least, it is not interpreted in this manner. But there are disk overflows which is different. The flattenning may be best explained as an indication of a non-standard disk where the disc may be warped by some mechanism. Note that the modelling is done with assumption of an optically thick disk and if the disk is optically thin with hot flows or some mixture of the two, divergence is expected (see LMXB eclipse maps).

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