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Disk Truncation and Structure in Nonmagnetic Cataclysmic Variables

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ABSTRACT
Cataclysmic variables (CVs) are close binary systems with a white dwarf (WDs) as the primary. They are excellent environments to study accretion flows, gas dynamics, outflows, transient outbursts, and explosive nuclear burning under a variety of astrophysical plasma conditions. I will discuss how flickering variability studies in X-rays can be probes to determine accretion history and spectra. Some CVs demonstrate band limited noise in the optical, UV and X-ray energy bands, which can be adequately explained in the framework of the model of propagating fluctuations. The frequency breaks of nonmagnetic systems in the range (1-6) mHz indicates an optically thick disk truncation allowing us to study disk structure, optically thick-thin disk transition conditions. The existing frequency breaks and time lags between X-ray and the UV show that accretion flows in the inner disks of nonmagnetic systems are advective hot flows. I discuss nonmagnetic CVs in terms of their broadband noise characteristics and extrapolate relations to XRBs (X-ray binaries) and AGNs (Active Galactic Nuclei).

1. Introduction

Cataclysmic Variables (CVs) and related systems (AM CVns, Symbiotics) are referred as accreting white dwarf binaries (AWBs). They are compact systems with white dwarf (WD) primaries. They constitute laboratories to study accretion flows, as dynamics, outflows, transient outbursts, and explosive nuclear burning. In CVs accretion is mostly through Roche Lobe overflow, thus disk accretion. CVs have two main categories. An accretion disk forms and reaches all the way to the WD 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 basic description in Warner, 1995; Balman, 2012; Balman, 2015; Mukai, 2017). The other class is the magnetic CVs (MCVs) divided into two sub-classes according to the degree of synchronization of the binary with the WD spin (Balman, 2019 and references therein).

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Dwarf novae (DNe) are a class of nonmagnetic CVs where matter is transferred by an accretion disk at a low rate (quiescence) and every few weeks to months or sometimes with longer durations as a result of an instability in the accretion disk, intense accretion (outburst) of days to weeks is observed where mass accretion rate increases to few $\times10^{-10}$ $M_{\odot}$/yr to a few $\times10^{-8}$ $M_{\odot}$/yr (Warner, 1995; Knigge et al., 2011). The total disk energy involved in the outburst of brightness is 10^{39}-10^{40} erg where the brightening changes in a range Δm=2-6 in magnitude. The DNe is divided into three major subclasses. U Gem types that have orbital periods over 3 hrs show no superoutbursts and more rare outbursts. Z Cam subtypes sometime experience standstills between the outbursts and the brightness never goes back to the original quiescence level. SU UMa subclass have orbital periods below 2 hrs and they show superoutbursts. The nonmagnetic high state CVs, namely nova-likes (NLs), are found mostly in a state of high mass accretion rate with a few $\times10^{-9}$ $M_{\odot}$/yr to a few $\times10^{-8}$ $M_{\odot}$/yr. They have winds that are about or less than 1% of the mass accretion rate, with velocities 200-5000 km/s (see Balman et al., 2014; Godon et al., 2017 and references therein). The last class of nonmagnetic CVs are the classical and recurrent novae. They are the third most violent explosion in the Universe after gamma-ray bursts and supernovae (10^{43}-10^{46} erg) due to explosive ignition of accreted H matter on the surface of the WD as the stable critical pressure is surpassed (see Bode & Evans, 2008 and references therein).

2. X-ray Emissions

X-ray spectral emission characteristics of DN in quiescence are a low accretion rate of M_{acc}=10-$^{10-12}$ $M_{\odot}$/yr ($L_x \approx 10^{28-32}$ erg/s) in line with the expected hard X-ray emitting optically thin boundary layers (BLs) in the standard model of disk accretion. The emission model is a multi-temperature isobaric cooling flow model plasma emission with T_{max} = 9-55 keV (see Balman, 2012; Balman, 2015 and references therein). However, the radiation inefficiency in the emission lines is about 1% of the emission from the continuum and the implied X-ray temperatures are virialized in contrast with the BLs in the standard accretion disk model. Virial temperatures in CV disks are 10-45 keV for a 0.4-1.1 $M_{\odot}$ WD (see Balman et al., 2014 for a discussion). DN outbursts are best explained with the DIM (Disk Instability Model; see Review by Lasota, 2001; 2004; Hameury et al., 2017 and references therein) and the new implications suggest that MRI and MHD calculations improve physics and relevance to observations and disk truncation should also be introduced (i.e., magnetic in the case for Hameury et al., 2017). The standard accretion disk model expectations in high state are M_{acc}=10^{-8} $M_{\odot}$/yr (Knigge et al., 2011) with optically thick BLs of 10^{5-6} K emitting in the soft X-ray to EUV (six detections with $kT \sim$ 5-30 eV) (see Balman, 2012 and references therein). The more conventional component detected in the outbursts is a low flux (compared to quiescence) of hard X-ray emission during the optical peak and throughout the outburst ($L_x \approx 10^{28-33}$ erg/s; McGowan et al., 2004; Collins & Wheatley, 2010; Fertig et al., 2011). During outbursts no eclipses or prominent orbital variations are detected. Radio emission from SS Cyg is interpreted as synchrotron emission originating from a transient jet and other radio detections (about six) of DN in outburst suggest existence of collimated jet-like outflows or flares as in XRBs (Körding et al., 2008; Russel et al., 2016; Coppejans et al., 2016).

At high mass accretion rates ($M_{acc} > 10^{-9}$ $M_{\odot}$/yr), as opposed to standard steady-state disk models, observations of nonmagnetic CVs (namely NLs) show a hot optically thin X-ray source as found in all observations with luminosities $\leq$ a few 10^{32} erg/s (Patterson & Raymond, 1985; van

Teeseling et al., 1996; Schlegel et al., 1995; Greiner, 1998). Later, some NLs were studied with *ASCA, XMM-Newton*, *Chandra* and *Swift*, yielding spectra consistent with double MEKAL models or multitemperature plasma models with yet again, $L_x \leq$ a few $\times 10^{32}$ erg/s (Mauche, 2002; Pratt et al., 2004; Page et al., 2014; Balman et al., 2014; Dobrotka et al., 2017). Balman et al. (2014) study conducted using *Swift* Observatory show that spectra of the three sources, BZ Cam, MV Lyr, and V592 Cas are consistent with a multitemperature plasma emission where the X-ray temperature is in a range kT_{max}=(21-50) keV and the X-ray emitting plasma is virialized. The ratio (L_x/L_{disk}) (L_{disk} from the UV-optical wavelengths) yields considerable inefficiency in the optically thin BL by ~0.01-0.001. Moreover, the power-law indices of the temperature distribution show departures from the isobaric cooling-flow-type plasma in equilibrium. They also suggest that a significant second component in the X-ray spectra of BZ Cam and MV Lyr that can be modeled by a power law emission. As a result, this detailed study on the three NL systems concluded that the BLs in NLs may be optically thin hard X-ray emitting regions merged with extended ADAF-like flows (advective hot flows) and/or constitute X-ray corona regions in the inner disk. A study of the archival *Chandra* HETG data of CVs shows that the X-ray line emission is consistent with multitemperature plasma in a nonequilibrium state (Schlegel et al., 2014) with n_e between 10^{12}-10^{16}/cm^3 which can be attributed to characteristics of advective hot flows.

3. Disk Structure and Broadband Noise

Some earlier flickering studies of CVs have been conducted using eclipse mapping techniques. These studies in quiescent dwarf novae indicate that mass accretion rate diminishes by a factor of 10-1000 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 expected from standard steady-state disks (e.g., Z Cha, OY Car, V2051 Oph and V4140 Sgr: see Balman, 2014 for a review). A comprehensive UV spectral 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) with the mass accretion rate decreasing 1-3 orders of magnitude in the inner disk region.

Another diagnostic tool to study the inner disk structure in accreting objects is the aperiodic variability of brightness (broadband noise) of sources. Long time-scale variability may be created in the outer parts of the accretion disk (Warner & Nather, 1971), but the relatively fast time variability (at $f >$ few mHz) originates in the inner parts of the accretion flow (see Balman, 2015; Bruch, 2000; 2015 and references therein). Properties of this noise is similar to that of the X-ray binaries with neutron stars and black holes. The 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; Ingram & van der Klis, 2013). Variations in the mass accretion rate as a result of fluctuations, 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. The optically thick accretion disks have a certain signature in broadband noise with a frequency index of $\nu^{-1-1.3}$ (Churazov et al., 2001; Gilfanov et al., 2005). This model predicts that the truncated optically thick accretion flow should lack some part of its variability at high Fourier frequencies. As a result, the frequency index should show a break into a steeper power law regime as the optically thick flow subsides. 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).

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) were calculated in terms of the fractional rms amplitude squared (Miyamoto et al., 1991) and integrated powers were used P_v versus n. 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 (PDS) show breaks in the variability with break frequencies in a range 1-6 mHz, indicating inner disk truncation of the optically thick accretion flow in these systems. The transition radii for DN are calculated in a range (3-10)×10^9 cm including errors (see Table 2 in Balman & Revnivtsev, 2012). Balman (2014; 2015; 2019) presents PDS analysis of five more DNe with the fitted break frequencies in the same ranges. Figure 1 shows the PDS of SS Cyg in quiescence and outburst.

The X-ray PDS analysis of SS Cyg in quiescence and outburst show that the disk moves towards the white dwarf during the optical peak to ~1×10^9 cm (~50 mHz) and recedes as the outburst declines to quiescence to 5-6×10^9 cm (~5 mHz) (see Balman & Revnivtsev, 2012 for details). This is shown for a CV, observationally, for the first time in the X-rays (see Figure 1 top left panel), also consistent with the theoretical calculation of Meyer & Meyer-Hofmeister (1994). The quiescence and outburst PDS of SS Cyg in the optical is also studied in Revnivtsev et al. (2012) and reveals very similar results to X-rays and does not reveal a clear break during the optical peak to around 0.1 Hz.

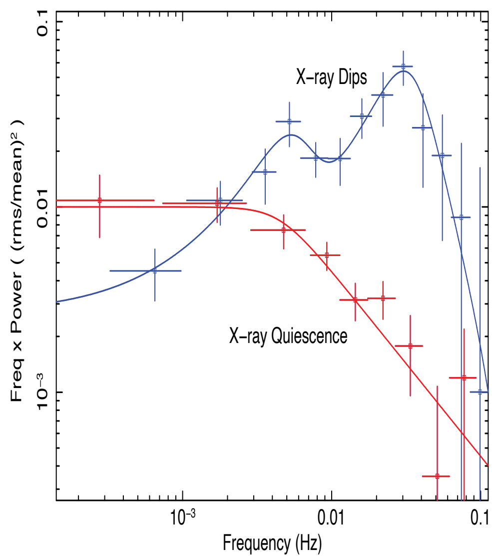

Figure 1. The X-ray PDS of SS Cyg in quiescence (red, *XMM-Newton* data) and outburst (Blue, *RXTE* data).

The UV and X-ray delays in the light curves and the anticorrelation of the hard X-ray and optical flux characteristics together with the decreasing hard X-ray temperatures during the outburst stage indicate that the quiescent accretion in DNe occurs through optically thin ADAF-like hot flows in the inner disk. Time lags detected in a range of 96-181 sec, are also consistent with matter propagation timescales onto the WD (Balman & Revnivtsev, 2012; Balman, 2019) in a truncated optically thick nonmagnetic CV disk in quiescence. Peaks near zerotime lag in four systems indicate that part of the UV emission may arise from reprocessing of the X-ray emission. An α parameter of 0.1-0.3 (for viscosity) 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 supported by radiation 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 (break frequencies around 0.1-0.2 Hz) during the optical peak of the outburst and the broadband noise reveals that the optically thick disk flow pulls out during the decline to a quiescent location.

4. Discussion and Results

The changes in the accretion rate in the disk has been associated with changes in the accretion geometry which in turn is described in state changes of the X-ray binary sources namely LMXBs. X-ray luminosity, spectral and PDS evolution can be studied during an outburst of the system over what is called a hysteresis curve/loop, firstly studied for BH LMXBs (Black Hole Low-mass X-ray Binaries) and later with all X-ray binaries (XRBs) (see Degenaar et al., 2018; Belloni, 2010) and finally for CVs (see Balman, 2019).

The Figure 2 shows a plot of the X-ray temperatures derived from the spectral fits and the break frequencies detected during quiescence and outburst (see left hand panel). The data are taken from the papers; Balman & Revnivtsev (2012) and Balman (2015; 2019) and references therein. The figure (see also Balman, 2019) indicates an anti-correlation between the X-ray temperatures and the break frequencies. The DN systems cluster at lower frequencies in quiescence and move towards higher frequencies during the outburst stage. This is an outcome of the optically thick disk structure that is truncated at larger disk radii and the optically thick disk moving in towards the WD as the accretion rates and densities increase in the disk during the outburst. Figure 2 (right hand panel, Balman, 2019) is a plot of the luminosity of the sources interms of Eddington Luminosity and the break frequencies. The figure shows on the y-axis the relative luminosities in the hard X-ray regime and that a broken power law relation is observed. In quiescence the luminosities increase with increasing break frequency as the optically thick disks reside more closer in the potential well of the WD. However, note that the flow is still advective (the relative luminosities being in the ADAF regime) and the X-ray emitting region in the inner disk is not fully radiative. The outburst shows a negative slope as the disk moves in during the outburst, relative luminosity diminishes and advection is stronger as the disk moves in and presses the hot flow structure towards the WD, decreasing temperatures and increasing densities. This could also explain the heating/cooling of the WDs during DN outbursts as the WD advects this retained energy in the flow (see also references in Balman et al., 2014; Balman, 2019).

In general, DNe broadband noise in quiescence and outburst show similarities to XRBs. The scenario of the accretion flow around a WD, resemble to that of BH and NS accretors with an optically thick colder outer accretion disk and an optically thin hot flow in the inner regions where the truncation/transition occurs (see review by Done et al., 2007). The appearance of a hot flow (e.g., ADAF-like flow) in the inner-most regions of the accretion disk will differ from that of standard rotating Keplerian disk because it is no longer fully supported by rotation with sub Keplerian speeds (observed in CVs as well), but have a larger radial velocity component. Balman et al. (2014) have shown that the X-ray emitting regions in nonmagnetic nova-likes are ADAF-like advective hot flows merged with boundary layers in a way similar to BH and NS LMXBs.

The X-ray spectral and timing studies reviewed here strongly indicates existence of ADAF-like advective hot flows in the inner regions of non-magnetic CVs where the optically thick flow structure truncates and the flow transits to a different structure. DNe show an anticorrelation of X-ray temperatures with break frequencies indicating that energy is exchanged in the X-ray emitting region within the disk structure (as revealed from the exponential time scale) and not radiated away from quiescence into the outburst. This shows the advective extended nature of the hot accretion flows in non-magnetic CVs, in general. In addition, optically thick disk truncation has also been detected for magnetic IP systems as a result of magnetic channeling, but the break frequencies are higher relative to the quiescent DN and the truncation radii are smaller. This may mean that the disk is more stable and persists on optically thick disk structure.

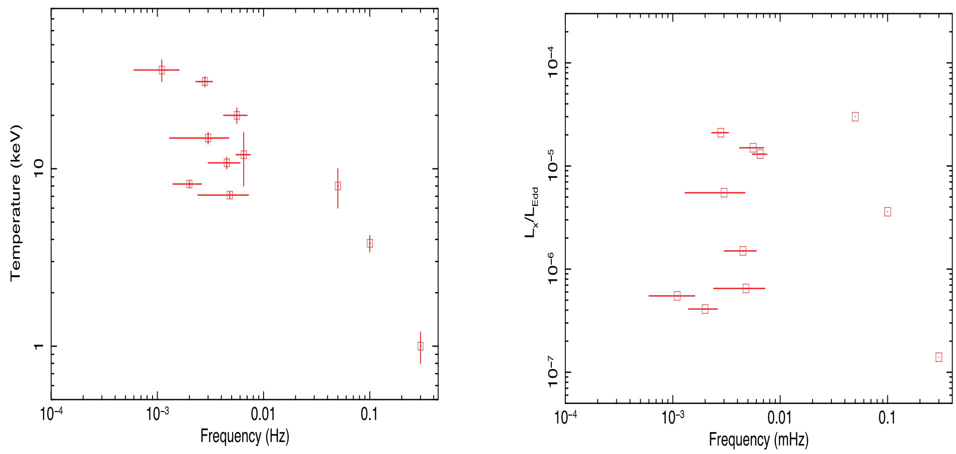

Figure 2. The break frequency versus X-ray temperature on the left and the X-ray luminosity versus break frequencies on the right for DN in quiescence and outburst.

Advective hot flows will have implications on CV evolution, as well. The WDs will be hotter since the retained heat from the disk will be radiated from the WD surface. This should also increase the level of irradiation of the secondary and possibly enhance the accretion flow from the secondary. However, the gravitational energy release will decrease since the energy is retained in the flow and not radiated (in the inner disk). This should slow down the evolution and/or stagnate it particularly above and below the period gap with a large group of sources stacked in the 3-4 hr range with hot WDs (as in NLs).

In general, disk truncation, as the accretion phenomenon, shows similarities across accreting systems hosting compact stars (extrapolated also to XRBs and AGNs hosting supermassive black holes and young stellar sources). However, each subclass (e.g. CV class) have their own differences as summarized in the review by Balman (2019) that needs to be taken into account to understand the physics of such accreting systems.

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