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Magnetic cataclysmic variables (CVs) versus non-magnetic CVs

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The factor which divides magnetic cataclysmic variables (CVs) from non-magnetic CVs is the strength B of the magnetic field (MF) of the white dwarf (WD). This paper shows on the examples of various CV types how this B influences the long-term activity. The increasing B influences first the X-ray emitting region by changing the accretion mode. In the intermediate polars, the time variations of the disk differ relatively little from those in the non-magnetic CVs, only the missing inner disk region caused by B of the WD makes the evolution of the dwarf nova outburst faster. On the other hand, accretion onto the polar caps of the magnetized WD produces a much harder X-ray emission whose intensity increases with the growing mass accretion rate. The changes of the mass transfer rate $\dot{m}$ are governed by the outflow from the donor, and they can cause the episodes of the low states in CVs no matter if they accrete via the disk or not. The current state of activity of CVs depends on their history especially if they contain the magnetized WD. The flaring intermediate polar AE Aqr is an example of the CV which became a propeller as a relict of the epoch of a very large $\dot{m}$.

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1. Introduction

Cataclysmic variables (CVs) are binaries with the orbital period $P_{\rm orb}$ typically of hours in which matter transfers onto the white dwarf (WD) from its companion (see Warner 1995 for a review). The factor which divides magnetic CVs from non-magnetic CVs is the strength B of the magnetic field (MF) of this WD. This strength plays a big role in setting the CV type because it strongly affects the flow and the structure of the transferring matter.

In non-magnetic CVs, the accretion disk reaches down to the WD. This matter forms boundary layer encircling the WD because it impacts almost tangentially. Large structural changes of this layer occur during transition between the states (Patterson & Raymond 1985). In CVs with mildly magnetized WDs ($B \approx 10^6$ Gauss), the so-called intermediate polars (IPs) (Warner 1995), the accretion disk is often present, but its inner region is truncated by the MF of the WD. Accretion curtains connecting the inner disk region and the regions at the magnetic poles (polar caps) of the WD cause an almost radial inflow. CVs with strongly magnetized WDs ($B > 10^7$ Gauss) are diskless systems (polars) and matter flows directly onto the polar cap(s) of the WD; all changes of the mass transfer from the donor are rapidly reflected in the observed properties of the system (Warner 1995).

The stronger the MF, the less room for the accretion disk is; this determines the observed properties and activity of CV. Accretion of matter gives rise to the largely different dominant emission processes: viscous heating of the accretion disk (if this disk is present) (UV, optical and IR thermal emission), cyclotron emission from the accretion column in polars (mainly optical and IR), and bremsstrahlung (the same process for all CV types, but originating from different emitting regions).

2. The magnetic field and activity of CVs

The MF has a strong effect on the spectral regions where emission from the accretion process dominates. Activity in the optical band for which we have abundant data is important for defining the CV type (e.g. dwarf nova (DN), novalike, polar) and the states of activity (e.g. outbursts, high or low state...).

The observable outcome of the modalities in the transferring matter is governed by the following processes: a thermal-viscous instability of the accretion disk (outbursts of DNe with the timescale of days, weeks, months); changes of the mass transfer rate $\dot{m}$ from the donor onto the WD (high and low states in novalike CVs and polars, with the timescale of days, weeks, months, years).

2.1 Outbursts of DNe

A thermal-viscous instability of the accretion disk (e.g. Hameury et al. 1998) plays an important role in the activity of CVs. It produces outbursts of DNe. This outburst begins when the accretion disk switches from the cold to the hot state after accumulating a sufficient amount of matter. This causes a strong increase of the temperature and viscosity of the disk matter, resulting in its accretion onto the WD at a large rate $\dot{m}_{\rm acc}$. In the optical band, the luminosity (representing thermal emission of the disk) increases by 2–5 mag, but the variations of X-ray luminosity (representing bremsstrahlung emission from boundary layer) are complicated and even largely differ from one

DN to another (compare e.g. Collins & Wheatley 2010 and Cordova & Mason 1984). These complex X-ray changes can be attributed to the large structural changes of the emitting regions (mainly boundary layer encircling the WD) between outburst and quiescence (Patterson & Raymond 1985).

For example, the X-ray spectrum of SU UMa/1RXS J081228.3+623627 (classified as a non-magnetic CV (Warner 1995)), observed in the 2–18.5 keV band of PCA/*RXTE*, gets softer and its luminosity fainter during the optical DN outburst. Collins & Wheatley (2010) attributed it to the changes of the structure of boundary layer from optically thin in quiescence to optically thick in outburst.

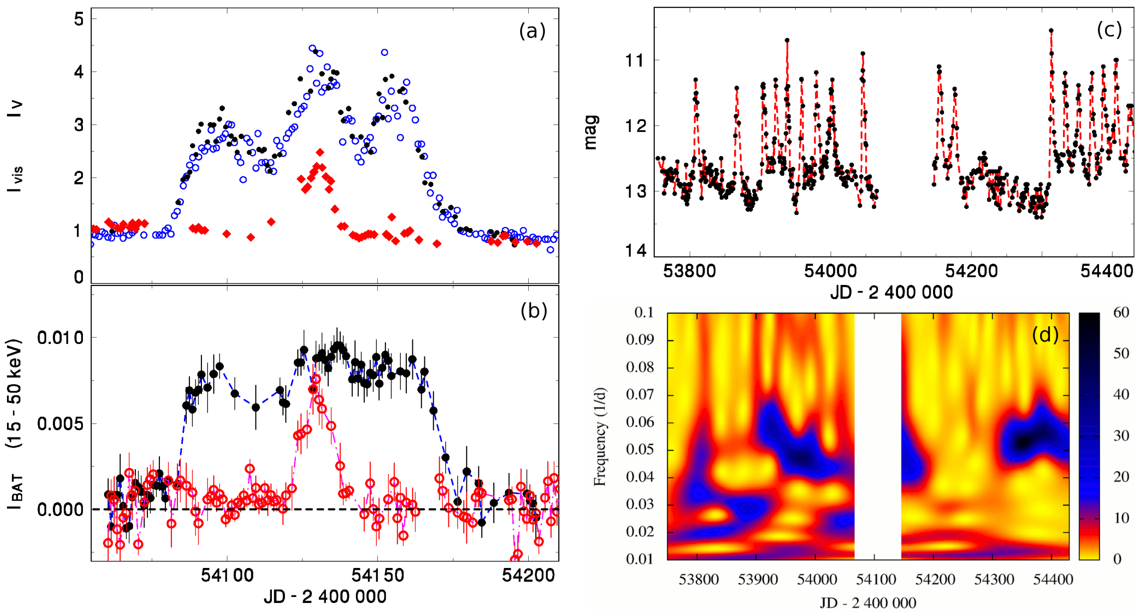

Figure 1: a) Two outbursts (long and short (shifted by −605 days)) of GK Per in the optical band (one-day means, intensity scale, intensity set to unity for the brightness of 13 mag) (data: AAVSO (Henden 2014)). Closed symbols: the V-band CCD measurements; open circles: visual data. **b)** One-day means of the BAT/*Swift* (15–50 keV) observations of the same two outbursts of GK Per (data: Krimm et al. 2013). **c)** Segment of the optical light curve of V426 Oph (one-day means of the visual and the V-band CCD observations) (data: AAVSO (Henden 2014)). **d)** WWZ-transform (the method of Foster 1996) of the light curve of V426 Oph from panel **c**. The color scale represents the values of WWZ. See Sect. 2.1 for details.

On the other hand, GK Per/2E 0327.7+4344 is an IP (Watson et al. 1985) and accretion from the disk occurs onto the polar caps of the WD, not via boundary layer. Because of the long $P_{\rm orb}$ = 1.99 d (Crampton et al. 1986), the accretion disk does not appear to be significantly influenced by the MF of the WD, but the increase of accretion onto the polar caps in a DN outburst leads to an increase of hard X-ray luminosity and to a further hardening of the X-ray spectrum of the bremsstrahlung emission (Ishida et al. 1992). Figs. 1ab show two DN outbursts with quite different profiles. The X-ray intensity in the 15–50 keV band (BAT/*Swift* (Krimm et al. 2013)) saturates during the longer outburst. Observations by ASM/*RXTE* in the 1.5–12 keV band (Levine et al. 1996), submitted to the procedure of the moving averages of intensities, gave the similar profiles as the data in the BAT band. Even the considerably fainter and shorter optical outburst can produce the

X-ray luminosity almost as high as the one in the plateau of the longer outburst. According to the model of DN outbursts (Hameury et al. 1998), the largest mass flow through the disk occurs in the time of the peak optical luminosity. This should lead to the peak of the X-ray luminosity radiated in the accretion regions at the polar caps of the WD, but the observed saturation of the X-ray intensity and its plateau do not correspond to it. This implies a discrepancy between the mass flow through the disk and $\dot{m}_{\rm acc}$ onto the polar caps of the WD. The deficiency of X-ray luminosity from the caps can suggest an outflow of part of the mass and/or the structural changes of the accretion regions at the polar caps of the WD (e.g. creating a depression in the WD by the accreting matter, as proposed for some polars with a very high specific mass accretion rate by Wickramasinghe & Ferrario 2000). Explanation by an increase of absorption at the caps is unlikely although Ishida et al. (1992) showed that X-ray absorption increases in outburst of GK Per, from log N_H(cm^{-2})$\approx$ 22 to $\approx$ 24. However, this increase of N_H cannot influence the intensity in the BAT (15–50 keV) band significantly to produce the plateau. Since the spin modulation of the WD was observed in the longer outburst in Fig. 1 by Evans et al. (2009), the accretion onto the caps is not replaced by accretion via boundary layer.

V426 Oph/1RXS J180751.8+055144 is classified as an IP according to the spin modulation of the WD in X-rays (Homer et al. 2004). Its optical brightness (both the mean level and the amplitude) is highly unstable on superorbital timescales (Fig. 1c). Frequent outbursts with the sharp peaks occur in clusters and are triggered only in the segments with the brighter quiescent level. While the DN outbursts are longer for DNe with longer $P_{\rm orb}$ and a given DN often displays alternating outbursts of two groups according to their length (van Paradijs 1983), the outbursts of V426 Oph belong only to the short-duration group. This is in accordance with the model of Angelini & Verbunt (1989) which predicts shorter outbursts if the inner disk region is truncated by the MF of the WD and the outburst is of the outside-in type.

Fig. 1d shows the results of a search for the recurrence time $T_{\rm C}$ of the outbursts in V426 Oph with the weighted wavelet Z-transform (WWZ). This method was developed by Foster (1996). WWZ indicates whether or not there is a periodic fluctuation at a given time at a given frequency f. The borders of the clusters of outbursts are relatively sharp and $T_{\rm C}$ does not undergo dramatically large variations. In the presented scenario, although the disk with the truncated inner region is usually in the low state, it is close to switching to the hot state; in occasional segments, only a small increase of the inflow into the disk is then sufficient to give rise to the cluster of short outbursts.

The effect of truncation of the inner disk region by the MF is even stronger in DO Dra/ 1RXS J114338.6+714125. It displays only infrequent strong but short outbursts with very steep decays (duration of $\sim$ 5 d, amplitude of $\sim$ 5 mag, $T_{\rm C}$ of hundreds of days (Šimon 2000)), in accordance with a thermal-viscous instability of the truncated disk modeled by Angelini & Verbunt (1989). Increase of intensity of both the thermal emission from the accretion disk and the bremsstrahlung emission during the outburst is attributed to accretion onto two poles of the magnetized WD (Szkody et al. 2002), so the increase of ram pressure of the disk is not strong enough to replace it by boundary layer.

2.2 Novalikes

Novalikes are CVs which spend most time in the state of the high $\dot{m}$, so their disks are resistive against the thermal-viscous instability (Warner 1995). In the optical high state, the observed intensity of their X-ray emission peaks at $E \approx 1-2$ keV, with a steep decline with growing E (Greiner 1998; Zemko & Orio 2013). The time evolution of this X-ray emission displays some controversy. This emission may come from a shocked wind or from accretion onto polar caps on the WD (Zemko & Orio 2013), although the given novalike may not be classified as an IP. The X-ray luminosity of novalikes usually decreases or becomes absent when these systems switch from the high to the low optical state, although this is the opposite in BZ Cam (Zemko & Orio 2013). This can suggest that various mechanisms producing soft X-ray emission can operate in novalikes.

Both MV Lyr/1RXS J190716.8+440109 (non-magnetic CV (Warner 1995)) and V1223 Sgr/ 1RXS J185502.1–310951 (IP (Steiner et al. 1981)) display a similar activity in the optical band (large-amplitude transitions between the high and low states (e.g. Greiner 1998; Garnavich & Szkody 1988; Šimon 2014)) while their X-ray spectra obtained in the optical high state largely differ (<0.5 keV blackbody in MV Lyr (Greiner 1998), bremsstrahlung with $kT_{\mathrm{max}} \approx 38$ keV in V1223 Sgr (Hayashi et al. 2011)) because of the different structure of the accretion regions. Truncation of the disk of V1223 Sgr by the MF makes its sustainment in the hot state by the viscous process more difficult. Although the accretion disk dominates the optical luminosity of V1223 Sgr in the high state, it is unclear how much the variations of the optical luminosity are due to viscous heating and how much reverberation of X-rays contributes (Beuermann et al. 2004).

Relating the intensities of the optical emission from the disk and the hard X-ray emission (15–50 keV) from the polar caps in V1223 Sgr gives an answer (Fig. 2ab). Even the relatively shallow optical low states (decreases by ~ 1 mag from the high state, much less than in the very deep low states discovered by Garnavich & Szkody 1988) are accompanied by significant decreases of the hard X-ray luminosity. This can hardly be attributed to an increase of absorption of such hard X-rays in these low states. Figs. 2ab thus show that the episodes of these optical low states are caused by decreases of the intrinsic X-ray luminosity. This suggests decreases of the mass inflow to the disk from the donor, and the resulting changes of $\dot{m}_{\mathrm{acc}}$. Nevertheless, changes of the medium reverberating the X-rays can play a role in modifying the relation of the X-ray and optical luminosities in the subsequent high states peaking in JD 2 454 300 and JD 2 455 050.

2.3 Polars

The observed activity of polars comes from the emission produced by several processes in a small accretion region on the WD (Kuulkers et al. 2006). Cyclotron emission is dominant in the optical band while bremsstrahlung dominates the medium and hard X-ray emission (with E even larger than 20 keV).

Variations of $\dot{m}$ govern the activity of polars. The variable structure of the accretion region and even variable modes of accretion (Heise et al. 1985) can play a role in explaining the long-term activity of the cyclotron and the bremsstrahlung components of AM Her/ 2E 1814.9+4951 (Šimon 2011). The properties of the hard X-ray emitting region are established in the beginning of the high-state episode. The luminosities of the cyclotron and the bremsstrahlung emissions are not tightly correlated and this relation can significantly differ for the individual, even consecutive, high-state episodes.

2.4 Propellers

Configuration of the accretion flow also depends on the evolutionary history of a CV. AE Aqr/

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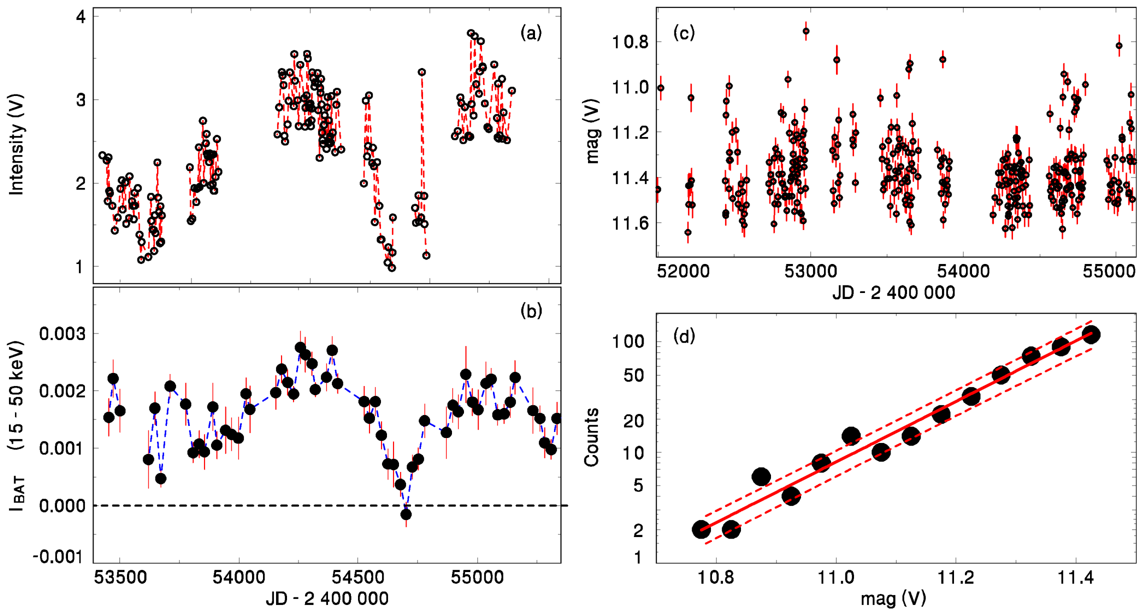

Figure 2: Relation of intensities of V1223 Sgr (IP) in the optical (ASAS data (Pojmanski 1997) (panel **a**) and the 15–50 keV X-ray (panel **b**) bands (arithmetic means (25 d bins) of the BAT/*Swift* data (Krimm et al. 2013)). **c)** Long-term optical activity (mostly a set of flares) of the propeller system AE Aqr (one CCD image per night, ASAS data (Pojmanski 1997)). **d)** Histogram of brightness of this set of flares. Only the activity in the levels of brightness in which only the flares, not the donor's tidal variations in between the flares, dominate, is considered. See Sect. 2.2 for details.

1RXS J204009.4–005216 is an important example. Now, it is an IP in a propeller regime: most of the transferring matter is ejected by the very rapidly spinning (33 s) magnetized WD (Wynn et al. 1997). This is the consequence of the phase of being a supersoft X-ray source with a very high $\dot{m}$; it spun up the WD by accretion onto it via the disk (Meintjes 2002). This is because the radius of the magnetosphere of the WD depends on the mass inflow rate: the propeller regime started when $\dot{m}$ decreased again.

Fig. 2c shows the current long-term activity of AE Aqr. The optical luminosity of the donor dominates only when the flare is not present. The emission of the optical flares, each of them lasting for minutes and causing a scatter of the light curve, is thermal (Pearson et al. 2003). Fig. 2d shows the statistical distribution of brightness of the whole set of flares (log-log in the intensity scale) only for the levels brighter than the donor. This histogram is remarkably different from the flat profile of the statistical distribution for a single flare (AAVSO CCD data (Henden 2014)). This suggests that the long-term activity of AE Aqr consists of the flares with remarkably different peak optical luminosities. Fig. 2d also shows that the flares of AE Aqr, thought to arise from the collisions between the regions in the material expelled from the CV after interaction with the rotating magnetosphere of the WD, obey a similar distribution as the infrared (K_s-band) flares from Sgr A*, the supermassive central black hole of our Galaxy, observed by Witzel et al. (2012). Meyer et al. (2006) linked the flares of Sgr A* to synchrotron emission from hot spots in the accretion disk near the last stable orbit of the black hole. The similar profiles of the statistical distribution of the intensities of the flares thus exist for dramatically different optical luminosities of the flares, the emission mechanisms, and the masses and the types of the central compact objects.

3. Conclusions

The character of the superorbital activity of CVs (and hence the CV type) in various spectral bands is strongly influenced by the value of B of the WD. This increasing B influences first the X-ray emitting region by changing the accretion mode: from boundary layer to radial accretion onto the polar caps of the WD. In the IPs, the time variations of the disk differ relatively little from those in the non-magnetic CVs, only the missing inner disk region caused by B of the WD makes the evolution of the DN outburst faster. On the other hand, accretion onto the polar caps produces a much harder X-ray emission whose intensity increases with the growing $\dot{m}_{\mathrm{acc}}$. The changes of $\dot{m}$ are governed by the outflow from the donor, and they can cause the low states in CVs no matter if they accrete via the disk or not. In this regard, De Bianchi et al. (2015) argued that in order to represent the roles of the magnetic field, it is needed to integrate the disk instability model by looking at the global behavior of the CV under analysis. In addition, the current state of activity of CVs with the magnetized WD depends on their history because dramatic increases of $\dot{m}$ in some evolutionary phases vary the spin period of the WD, leading to the large changes of the accretion mode.

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PoS(FRAPWS2014)011

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PoS(FRAPWS2014)011