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Observing cataclysmic variables and related objects with different techniques

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Abstract. We review the lines of evidence that cataclysmic variables (CVs) can be radiators over a very broad range of wavelengths, from gamma and far X-rays to radio. Only observations in various spectral regions enable us to identify and study various emission mechanisms (bremsstrahlung, thermal, cyclotron, synchrotron) and their mutual relations during the accretion process in CVs. The roles of the individual emission mechanisms depend on the mode of the mass transfer (given e.g. by the strength of the magnetic field of the white dwarf (WD)) and on the state of activity. The long-term activity of CVs in the optical band appears to be a plausible indicator of the mass accretion onto the WD in most non-magnetic and magnetic CVs. The data coverage in other bands is often fragmentary or even absent. We therefore recommend using the optical activity as the guiding line and correlating the observations obtained in other bands with the state of the optical activity. While an increase of the mass accretion rate onto the WD leads to an increase of optical luminosity, a complicated relation between optical emission and radiation in other bands (e.g. X-ray) exists; the correlations can differ for the individual CVs even of the same subtype. The structure of the accretion regions plays a role here. Some phenomena of an unclear origin have episodic character with a very small duty cycle (e.g. flares in some intermediate polars); this makes their detection and establishing the relation of the behavior in various bands (hence the relation between various emission mechanisms) very difficult.

Key words. X-rays: binaries – circumstellar matter – accretion, accretion disks – novae, cataclysmic variables – Radiation mechanisms: general

1. Introduction

In cataclysmic variable (CV), matter flows from a companion star, the so-called donor, onto the white dwarf (WD). This mass-transferring binary is a complicated and very active system with various emission regions with a complicated structure. Although CVs were often discovered in the optical band and most data come from this spectral region, they have been shown to radiate in various spectral regions via various emission mechanisms. The complicated structure of the emission regions and of the resulting spectral energy distribution (SED) largely varies with the state of their long-term activity. Review can be found in Warner (1995). CVs are therefore very important laboratories for the study of the physical processes with various techniques.

Several mechanisms can govern the long-term activity of CVs (changes of the mass

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transfer rate $\dot{m}$, thermal-viscous instability of the accretion disk, hydrogen burning on the WD). Each of these mechanisms influences the emission of CV in various spectral regions. We will discuss them in this paper.

2. Activity of various types of CVs

2.1. Systems with outbursts

In some CVs, the accretion disk suffers from a thermal-viscous instability if $\dot{m}$ lies between certain limits. It gives rise to the large-amplitude (even more than 5 mag) optical outbursts in the so-called dwarf novae (DNe) (e.g. Hameury et al. 1998). These events are accompanied by the complicated variations in other spectral regions.

The time evolution of outbursts in DNe VW Hyi, SU UMa, and SS Cyg was observed to display remarkable similarities in the complicated relation between the behavior in the optical, UV (*IUE* and *EUVE* satellites), and X-ray (*ROSAT*, *RXTE*, *Ginga*) bands (Wheatley et al. 1996; Collins & Wheatley 2010; Wheatley et al. 2003). A strong dependence of the outburst profile on the spectral region was observed. The interpretation is that optical and X-ray emissions come from different regions in the system. While optical and UV emissions come from the accretion disk, extreme UV and X-ray emissions originate from the boundary layer. This multispectral mapping enables to state that large structural changes of the emission regions (especially in the vicinity of the WD) occur during the outburst. The boundary layer changes from optically thin, geometrically thick to optically thick, geometrically thin during this event. Its spectrum gets softer during this transition. Repeating X-ray variations in a series of normal outbursts in SU UMa even enabled to achieve more general conclusions about its long-term activity.

As regards the behavior of hard X-ray ($E >$ 2 keV) flux during the start and end of a DN outburst, some uncertainties exist. Spikes of hard X-ray flux are observed during the bottom part of transition in SS Cyg as expected (Wheatley et al. 2003). However, these spikes are missing in normal outbursts of SU UMa. Two explanations were proposed by Collins & Wheatley (2010). The quiescent accretion rate was already close to the critical value before the outburst or the spike was very short and thus missed.

The importance of far UV observations of the rising branch of outburst was shown by Polidan & Holberg (1987). They combined ground-based optical and far UV (1050 Å) *Voyager* data of the same normal outburst of VW Hyi. The UV rise was delayed by ~0.5 day with respect to the optical one. Mapping these spectral regions is important for the study of the thermal instability of the accretion disk, namely of the propagation of heating front across the disk. Optical emission mostly comes from the middle and outer disk region. On the other hand, far UV emission originates from the inner disk region. The observed delay was caused by the fact that heating front bringing the disk from the cool to the hot state began in the outer disk region and propagated inward. No such UV delay was observed during the decay of the outburst since cooling front always begins in the outermost radius of the disk region previously brought to the hot state.

It is very important that SS Cyg was detected as a radio source during its DN outburst (Körding et al. 2008). A comparison of the hardness vs. intensity diagrams for various types of mass-accreting objects in outburst showed that the radio flare occurred during the same phase as in the outbursting systems with the neutron star and black hole accretors. Radio emission of SS Cyg did not directly follow the optical one. The radio-emitting medium was thus not any detached reprocessing medium; it originated directly from SS Cyg during the outburst. Size of the radio-emitting medium was greater than the CV, and it was much larger than the magnetosphere of the WD. Radio emission of SS Cyg was thus synchrotron radiation of a transient jet. This lead to the conclusion that SS Cyg became a member of the family of microquasars (Mirabel & Rodríguez 1999). It represents a link between jet-showing systems containing various types of compact objects.

GK Per/1A 0327+43 is a remarkable CV. This intermediate polar undergoing DN outbursts is one of a very few CVs detected by the all-sky X-ray monitor ASM/*RXTE* (1.5–12 keV) (Levine et al. 1996). This enables us to find a more general relation between the optical and X-ray evolution of the outburst for the individual events. The X-ray start of the outburst can precede the start of the optical one by up to 40 days in this system (Bianchini & Sabbadin 1985) but this varies for the individual events. This is because each of the later outbursts in 1996, 1999, and 2002 (Šimon 2002, 2003b) started simultaneously in the optical and ASM X-ray band. ASM data often showed a plateau or even a depression of X-ray intensity during the sharp peak of the optical outburst. Two mechanisms which can even operate simultaneously are promising: X-rays blocked by a thickened disk and accretion curtain near the optical peak (Yi et al. 1992), and radiation drag (Yi & Vishniac 1994).

In addition, GK Per has recently proved to be an exceptionally hard X-ray source among DNe because it was detectable by BAT/*Swift* (15–50 keV) during its three mapped outbursts. The rise of optical and far X-ray flux repeats for the individual outbursts, although the correlation of the profiles is complicated (Fig. 1). This is a way toward establishing the general properties of the accretion regions in this CV. In spite of a seasonal gap, Fig. 1 shows that the time of the optical peak does not coincide with that of the X-ray one. We can constrain the physical models since extinction is not important in the BAT X-ray band. Radiation drag can thus play a role although it cannot fully explain the relation itself.

Rare brightenings in DO Dra are another example of DN outbursts in intermediate polar. Hard X-ray (PCA/*RXTE* 3–10 keV) emission increased by more than a factor of 12 during the outburst. Time evolutions of optical (from the disk) and hard X-ray (from the accretion regions on the WD) flux were in accord. Accretion from the disk onto two magnetic poles of the magnetized WD occurred during this event (Szkody et al. 2002).

In addition, there is a yet unknown component of matter in at least some CVs (Howell et al. 2008). This thermally radiating component was observed in WZ Sge in the microwave band in quiescence by *Spitzer* satellite. It represents an additional structure in the lobe of the WD. Gaseous accretion disk is surrounded by an asymmetric disk of dusty material concentrated on the side toward the donor. This dust ring contains only a small amount of mass and is completely invisible at the optical and near-IR wavelengths because of its low temperature ($T \approx 700 - 1500$ K). It is not known how this dust component behaves during outburst and whether it influences it.

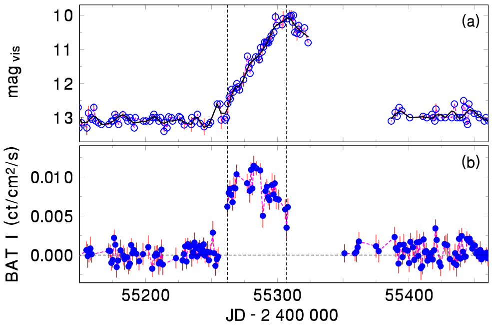

Fig. 1. The optical (AFOEV) (a) and the BAT/*Swift* (15–50 keV) X-ray light curve (b) of the outburst in GK Per. The smooth line represents the HEC13 fit. The times of the onset and peak of the optical outburst are marked.

It emerges that large structural changes of the accretion region which occur during transition from quiescence to outburst play a great role. These structures strongly depend on the strength of the magnetic field of the WD. In CV with a relatively non-magnetic WD, accretion of the disk matter proceeds onto the equatorial region of the WD, where it forms the boundary layer. During a DN outburst, this layer changes from optically thin, geometrically thick to optically thick, geometrically thin and its effective temperature $T_{\rm eff}$ decreases (Patterson & Raymond 1985). Some intermediate polars, i.e. CVs with a mildly magnetized WD (typically $B < 10^7$ G) (e.g. Warner 1995) possess the accretion disks, too (e.g. GK Per and DO Dra). However, their inner regions are truncated by the magnetic field of the WD. Matter from the disk flows toward the accretion regions at the magnetic poles of the WD via accretion columns (e.g. Warner 1995). The bottom part of such a column is a source of hard X-rays even during outburst.

2.2. Flares in intermediate polars

Some intermediate polars were observed to display brief brightenings which cannot be explained by a thermal-viscous instability of their disks. V1223 Sgr/1H 1853–312 is an example. One flare with an amplitude of more than 1 mag in the red continuum lasted only for several hours. It was accompanied by an increase of the Hα line flux and equivalent width, which was longer than in the continuum. This suggests that also the line emission participated in this event (van Amerongen & van Paradijs 1989). Another flare (> 1 mag) was found on an archival photographic plate (Bamberg) in blue light (Šimon 2010). This event occurred during a shallow low state, but still from the level much brighter than the true low states (Garnavich & Szkody 1988). The third flare was observed in far infrared (14–21 μm) by *Spitzer* satellite. The flux declined by a factor of 13 in 30 minutes. This far IR event suggests a transient synchrotron emission (Harrison et al. 2010).

Three flares were thus detected in V1223 Sgr, but each of them with a different technique. It is thus not known what happened in various spectral regions during the flare and whether all these flares were caused by the same emission mechanism. The reason is the lack of multiwavelength data coverage (since the flare is rare). The flare observed by *Spitzer* has a very flat spectrum in far IR. An extrapolation of the flux of this flare to the optical band cannot explain the observed optical flares. Several possibilities exist. The optical brightenings might be caused by the extremely strong synchrotron flares. However, an interaction of the inner disk region with the synchrotron jet (or bubble) is supported by an increase of the Hα emission during the flare.

Several flares were also observed in the intermediate polar TV Col/1H 0527–328. The long-term activity studied in photographic data (blue-band) revealed that its character remains very similar on the timescale of years, with occasional flares from an almost stable quiescent level (Hudec et al. 2005). A combination of *IUE* and optical observations of one such event enabled to show that power-law and blackbody components satisfy SED between far UV and the *V* band for the peak of the flare (Szkody & Mateo 1984). This flare was associated with a hot inner disk event because of a steepening of the power-law component and an increase of the temperature. A UV power-law fit to SED was explained as the tail end of blackbody from the WD flattened by an addition of the UV flux from the disk. This flare was attributed to an increase of dumping of material onto the accretion pole. Since the UV and optical flux rose together, the flare originated close to the WD surface.

2.3. High and low states in novalike CVs

Even CVs with the high time-averaged $\dot{m}$ (the so-called novalike systems), hence with their hot, thermally stable disks, display strong activity. Especially transitions between the high and low states attributed to the variations of $\dot{m}$ are very important. Only multifrequency observations can provide us with information about the controversial behavior of these systems during these transitions. We list two cases, MV Lyr and V751 Cyg. The drop of $\dot{m}$ lead to a decrease of optical brightness of both systems, but the accompanying behavior of soft X-ray flux was quite controversial.

MV Lyr displays a long-term activity with episodes of the high and low states in the optical band (Fig. 2). *ROSAT* detected it in the soft X-ray band only in the optical high state (Greiner 1998). This X-ray emission with < 0.5 keV blackbody spectrum was similar to that of other novalikes of VY Scl type. The X-ray flux dropped by a factor of $> 5 - 7$ during the optical low state (Fig. 2). This suggests that the drop of the X-ray flux is related to a decrease of $\dot{m}$. This X-ray emission must have come from the accretion process since coronal emission of the donor is ruled out.

A combination of ultraviolet (*IUE* satellite) and optical (ground-based) data showed different dominant emission components of the flux distribution in various states of activity of MV Lyr. In the optical high state, the light of

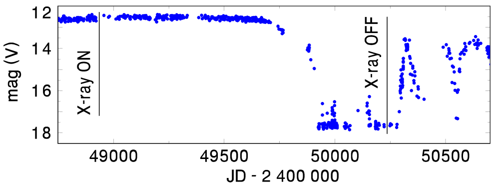

Fig. 2. Relation between the state of the optical activity and the detection of soft X-ray emission in the novalike system MV Lyr. Adapted from Greiner (1998). The optical data (AAVSO): Henden (2011).

the accretion disk ($\dot{m} \approx 10^{-9}$ $M_\odot$ yr^{-1}) dominated in the UV, optical, and near IR bands (Szkody & Downes 1982). In addition, recent *FUSE* data (< 950 Å) showed a contribution of the boundary layer at the inner disk edge ($T_{\mathrm{eff}} \approx 100\,000$ K) and of the WD ($T_{\mathrm{eff}} > 50\,000$ K) (Godon & Sion 2011). During the optical low state, the spectral slope changed considerably. UV emission was dominated by that of the WD ($T_{\mathrm{eff}} \approx 50\,000$ K). In the optical band, the accretion disk with a very low $\dot{m} \approx 5 \times 10^{-11}$ $M_\odot$ yr^{-1} dominated. Even the donor contributed in the red region (Szkody & Downes 1982).

In variance with MV Lyr, V751 Cyg displayed a clear anti-correlation of X-ray and optical intensity. In the optical low state, its soft X-ray flux measured by *ROSAT* increased by a factor of 7–19 with respect to that in the optical high state (Greiner et al. 1999). V751 Cyg thus became a transient luminous supersoft X-ray source with $L_X \approx 10^{34} - 10^{36}$ erg s^{-1} during the optical low state. UV *(IUE)* and optical data showed that the mass transfer was lower during these X-ray detections, but it was not stopped.

Since the intermediate polar V1223 Sgr is a very hard X-ray source among CVs, its long-term activity could be mapped in far X-rays by IBIS onboard *INTEGRAL* (integration time of 67 000 s per mosaic) (Šimon et al. 2006). It mapped a lower than average level of the typical high-state brightness (shallow low state). SED in the 15–60 keV band proved to remain largely unchanged during this state for ~400 days. A combination with the *V* band OMC/*INTEGRAL* data enabled to relate the processes in different regions of this CV: the accretion disk (the optical band, thermal emission) vs. the impact regions near the magnetic poles of the WD (X-rays, bremsstrahlung (Revnivtsev et al. 2004). It revealed good stability of luminosity in these bands, hence good stability of the accretion process in a shallow low state.

AE Aqr is unique system because it is intermediate polar in a propeller regime. Most of the transferring matter is ejected by the rapidly spinning (33 s) magnetized WD (Wynn et al. 1997). Synchrotron emission from electrons in expanding clouds dominates in far IR and radio bands, but a contribution of thermal emission from cold circumbinary material is possible, too (Dubus et al. 2007). Optical and radio flares are not strongly directed toward any preferred direction in the frame of the binary. Occurrences of flares are not correlated, which suggests that two independent processes operate (Abada-Simon et al. 1995). AE Aqr is a transient TeV source detected by ground-based Cherenkov telescopes (Meintjes et al. 1992, 1994). Optical and TeV flares display the same frequency (33 s spin period of the WD). Duty cycle of TeV flares is small (0.2 percent). These TeV flares were interpreted as due to acceleration of particles by the rotating magnetic field of the WD in intermediate polar in the propeller regime. TeV flares occur only during a low optical brightness; the accretion luminosity must be low to allow the disk inner edge radius to be outside the co-rotation radius. Electrons are accelerated to $E \approx 10^{13}$ eV and converted to gamma-rays via π^{o} decay in the blobs.

2.4. Supersoft X-ray sources (SXSs)

Supersoft X-ray binary sources (SXSs) are unique binary systems in which the mass transfer onto the WD occurs at a very high rate ($\dot{m} \approx 10^{-7}$ $M_\odot$ yr^{-1}). This allows steady-state hydrogen burning on the WD (van den Heuvel et al. 1992; Hachisu & Kato 2003). Intense soft X-ray emission is produced, but its detectability depends on interstellar extinction and metallicity of the source. Optical emission comes from both the reprocessing off X-rays in the disk and from the disk viscosity. Strong activity in various spectral bands is common.

Optical luminosity of V Sge varies in antiphase with soft X-ray luminosity measured by *ROSAT* due to an increase of X-ray absorption (Greiner & van Teeseling 1998). It turns into supersoft X-ray source only during its optical low state. On the other hand, it is X-ray faint and hard source during the optical high state. The features of activity were interpreted in terms of accretion wind evolution by Hachisu & Kato (2003). V Sge displays a very complicated long-term optical activity; the character of activity changed considerably during about 40 years (Šimon & Mattei 1999). X-ray observations map only a short time segment of this activity.

SXSs can be radio emitters, as documented by V Sge. It was detected as a radio source in its optical high state (λ = 2 cm, 3.6 cm, 6 cm) (Lockley et al. 1999). Radio flux was variable on long timescales (1996 vs. 1998). It was a mixture of both thermal and non-thermal emission. It was ascribed to colliding winds from the donor and the accretor, not to a collimated jet. It is not known how it depends on the state of activity.

The long-term activity of RX J0513–69 is similar to that of V Sge (Cowley et al. 2002). It displays recurring episodes of high/low state transitions. The behavior of the source in the optical *(MACHO)* and X-ray *(ROSAT HRI)* bands is very similar to V Sge – optical luminosity varies in antiphase with soft X-ray luminosity. The source is undetectable in soft X-rays during the optical high state. This behavior was explained by the radius changes of the WD envelope between the states (Reinsch et al. 2000).

A comparison of the $(U-B)_0$ vs. $(B-V)_0$ diagram with the plot of the optical absolute magnitude M_V vs. bolometric luminosity $L_{\rm bol}$ (from X-ray spectra) provides us with information about the behavior of SED of SXSs from the X-ray to the optical band. Most SXSs with the orbital period $P_{\rm orb} < 4$ d form a closed group in this color-color diagram. Hot continuum (accretion disk?) with very similar properties in the individual SXSs thus dominates in the optical spectral region. Some SXSs are above the curve of black bodies, which suggests a contribution of an optically thin hot medium. Great mutual similarity of the optical color indices contrasts with big scatter of the $M_V - L_{\rm bol}$ ratio (Šimon 2003a). It is thus likely that even yet undiscovered SXSs can be intense emitters of optical radiation even at a low X-ray flux.

2.5. Polars

Polars are CVs with a strongly magnetized WD (typically $B > 10^7$ G (e.g. Warner 1995). No disk is formed and matter therefore flows directly onto the accretion region(s) at the magnetic pole(s) of the WD. The accretion column radiates via cyclotron mechanism in the optical and near IR bands, while the accretion shock emits bremsstrahlung in hard X-rays (E up to 100 keV). Heated region of the WD near the pole emits mainly far UV and soft X-ray thermal radiation ($E < 1$ keV) (e.g. Gänsicke 1997).

A relation between the optical and hard X-ray (1.5–12 keV) light curves in the individual high-state episodes of AM Her/3A 1815+498 is shown in Fig. 3. According to Kuulkers et al. (2006), this corresponds to a relation between the cyclotron and bremsstrahlung components. It emerges that the properties of the emission region(s) on the WD are established in the beginning of the high-state episode. An increase of $\dot{m}$ establishes a division of the emission released during the accretion process into various spectral regions; this division is valid only for a given episode (Šimon 2011).

AM Her is a radio source (4.9 GHz) (Dulk et al. 1983). Several sites of radio emission existed in the same time (the optical low state). Quiescent radio emission was ascribed to the energetic electrons trapped in the magnetosphere of the WD. Radio outburst (flare) was explained as an electron-cyclotron maser near the surface of the late-type donor.

SED for six polars using the data from *Spitzer* satellite and 2MASS showed that a circumbinary dust disk is the most likely cause of the 8 μm emission (Brinkworth et al. 2007). The mass of this disk is low and does not affect CV evolution. Neither dust nor cyclotron emission alone can match the excess above the stellar components at all wavelengths, A combina-

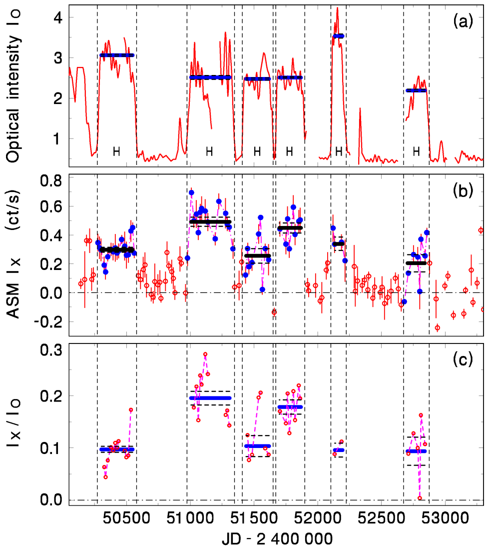

Fig. 3. Part of the optical (AFOEV) (a) and the ASM/*RXTE* X-ray light curve (b) of AM Her. Only the HEC13 fits are shown for the optical band. The dashed vertical lines denote the crossing of the level of 14.3 $\mathrm{mag_O}$. The 15-day means of I_X are displayed for ASM data. (c) The X-ray to optical intensity ratio. Adapted from Šimon (2011).

tion of several processes is required: cyclotron, dust, and accretion-generated flux.

3. General conclusions

It emerges that CVs can be radiators over a very broad range of wavelengths, from gamma and far X-rays to radio. Observations in various spectral regions enable us to identify and study various emission mechanisms during the accretion process in CVs. The roles of these mechanisms depend on the magnetic field of the WD and on the state of activity of the system. Only multifrequency observations enable us to investigate the mutual relations between these mechanisms.

The configuration of the X-ray emission region strongly depends on the strength of the magnetic field of the WD and on the state of the CV (e.g. quiescence vs. outburst, low state vs. high state). Bremsstrahlung is often the source of this emission. It usually comes from the vicinity of the WD (the boundary layer in non-magnetic CVs, the polar cap(s) in magnetic systems). The mechanism is different in SXSs; a very hot atmosphere of the WD dominates (van den Heuvel et al. 1992).

Thermal emission from the inner disk region (and from the boundary layer for certain mass accretion rates) dominates in the ultraviolet band in the case of disk accretion. Also the WD heated by the boundary layer is a source of UV radiation. In polars, UV emission originates e.g. from heating of the WD by accretion near the magnetic pole(s).

In the optical band, the disk accretion leads to thermal emission. Viscous heating of the disk matter dominates. However, reprocessing off X-rays from the WD in the disk and the donor plays a great role in SXSs. In polars, cyclotron emission from the accretion column dominates.

Thermal emission of the dust (either in the WD's lobe or circumbinary) is important in far IR (from several μm to mm). This dust represents a yet unknown component of CV.

Radio emission is produced by several mechanisms. It can come from various CV components. The configuration of the emission region depends on the CV type. Synchrotron emission provides us with evidence of generation of the magnetic field(s). It can come from the jets launched during the outbursts of DNe. DNe thus became the members of the microquasar family. Synchrotron-emitting clouds launched from the system were proposed for AE Aqr. In the case of the polar AM Her, several emission regions operating simultaneously (e.g. flares from the donor's magnetosphere) were observed.

The long-term activity of CVs in the optical band appears to be a plausible indicator of the mass accretion onto the WD in both non-magnetic and magnetic systems. On the other hand, the data coverage in other bands is fragmentary or even absent. We therefore recommend using the optical activity as the guiding line and correlating the observations obtained in other bands with the state of the optical activity.

It emerges that an increase of the mass accretion rate onto the WD (but not of the mass transfer rate) leads to an increase of optical luminosity. However, a complicated relation between optical emission and radiation in other bands exists; precise correlations are more or less valid only for a given CV. Structural changes are very important; a plausible relation between the behavior in the optical and X-ray bands is mostly valid only for a single CV. Control of the accretion flow by the magnetic field of the WD plays a great role and may not be easily recognized in intermediate polars (a very fuzzy transition between magnetic and non-magnetic WDs may exist).

Some phenomena have episodic character with a small duty cycle. This regards e.g. ultra-high energy flares in propeller systems (AE Aqr) and radio flares in polars (AM Her). This episodic character and hardly accessible instruments for monitoring make establishing the relation of the behavior in various bands (hence the relation between various emission mechanisms) very difficult.

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