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Long-term activity of cataclysmic variables

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We show examples of the long-term optical activity of various types of cataclysmic variables. Episodic events are the common properties of this activity which often consists of the discrete levels of brightness and/or discrete phenomena (e.g. outbursts, low state episodes). The length of the recurrence time T_{C} of the outbursts in dwarf novae (DNe) displays complicated time changes. This suggests that the individual outbursts of a given DN depend on each other, and only a small fraction of the disk matter is accreted in a given outburst. The processes in the cool disk (between the outbursts) play a big role in DNe. The low states in novalikes and polars often occur in clusters. The state transitions sometimes occur in intermittently present cycles. In the interpretation, changes of the position of the active regions on the donor with respect to the L1 point by a differential rotation of the donor are suggested. The short high states, surrounded by the long low states, can be explained by isolated bursts of mass transfer from the donor. EI UMa is an example of the intermediate polars whose brightness can largely fluctuate on the timescale of days and also produce flares. Large changes of the mode of accretion (flares, shalow low states) occur in a similar brightness of EI UMa, hence in a similar mass accretion rate onto the WD. The long-term activity of propellers depends on the configuration of the magnetic field of the white dwarf; this activity of AR Sco, with the luminosity comparable to the deep and very long (at least several decades) low states of novalikes, is dominated by a strong orbital modulation of synchrotron emission.

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1. Introduction – mechanisms driving the emission of CVs

Cataclysmic variables (CVs) are close binary systems in which matter transfers onto the white dwarf (WD) from its companion, a lobe-filling star (donor) (e.g. [63]). In most cases, this transfer of matter is caused by a decrease of the orbital period $P_{\rm orb}$.

Gravitational radiation and magnetic braking are the causes of a decrease of $P_{\rm orb}$ on the evolutionary timescales of most CVs. Gravitational radiation is important because CVs have very short $P_{\rm orb}$ (usually from minutes to hours, the CV with the shortest $P_{\rm orb}$ of 5.4 min is HM Cnc [40]). Above the so-called period gap (e.g. [63]), magnetic braking is cased by outflow of the donor's wind along the field lines of the magnetic field of this late-type component.

The above-mentioned mechanisms provide the basic framework of the mass transfer but the observed activity of CVs (the optical observations span over about 100 years in some cases) is more complicated: processes in the transferring matter (the accretion disk); variable mass outflow from the donor toward the WD; thermonuclear reactions of the accreted matter on the WD.

The detection of the optical radiation of CVs enables analyses of the densely populated long-term light curves (e.g., tens of years). This provides information about the processes in the dominant emission regions (mainly thermal emission in CVs with the accretion disk, cyclotron emission in polars (diskless CVs with strongly magnetized WD)). Other emitting components (e.g., the WD and the donor) are observable only in some cases like the low states of novalike CVs [39, 56], and quiescence of some dwarf novae (DNe) with short $P_{\rm orb}$ [10].

2. Observations

The digitized photographic data were obtained from Digital Access to a Sky Century @ Harvard (DASCH)[1] [11, 12]. This database provides SExtractor-based photometry of every resolved object. The band of these data can be approximated by the *B*-band.

Also visual and *V*-band CCD observations from the AAVSO International database (USA) [17, 22, 23, 24], CCD Catalina Real-time Transient Survey (CRTS) [3] observations (the *V*-band), and CCD *V*-band observations of the ASAS-3 project [2] [34] were included.

3. Long-term activity of various types of CVs

We present examples of the long-term optical activity of the individual types of CVs. Of course, this short paper does not draw any conclusions about generalized long-term behavior of CVs.

3.1 The dwarf nova RU Peg

Dwarf novae (DNe) display outbursts that are interpreted in terms of the thermal-viscous instability of the accretion disk (e.g. [46, 14]), leading to episodic accretion of matter from the disk onto the WD. The outburst is caused by a transient transition of the disk from the cool state to the

[1] http://dasch.rc.fas.harvard.edu/lightcurve.php
[2] http:// archive.princeton.edu/∼asas

hot state when the column density of matter accumulated in the accretion disk reaches a critical value.

RU Peg is classified as a U Gem-type DN [27, 41]. A series of the DN outbursts of RU Peg is displayed in Fig. 1a. The light curve shows a series of outbursts whose peak magnitudes significantly vary while the quiescent brightness shows only minor changes.

The method of O–C residuals of some reference period (see [60]) enables us not only to determine the recurrence time T_C of the outbursts, but also to analyze its variations. Figure 1b shows that the length of T_C in RU Peg is variable, but the occurrence of these outbursts is not dramatically irregular. This suggests that the individual outbursts depend on each other. This behavior can be explained if only a small fraction of the disk matter is accreted in a given outburst. The processes in the cool disk (between the outbursts) play a big role in the evolution of T_C.

This time evolution of the series of outbursts and the O–C curves of RU Peg are similar to those in other DNe (e.g. [60, 49, 50]).

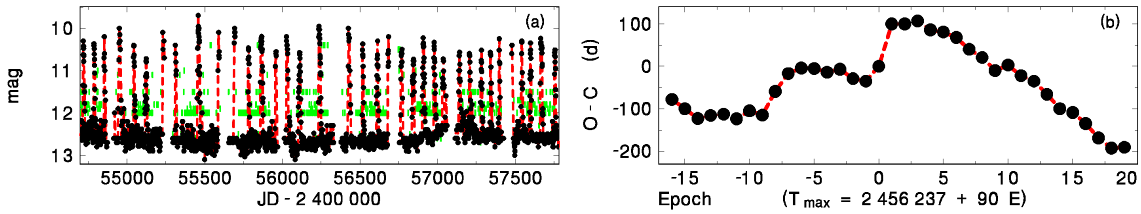

Figure 1: (a) Series of DN outbursts of RU Peg. The AAVSO one-day means are used. The short vertical lines mark the upper limits of brightness if RU Peg was below the detection limit. **(b)** O–C diagram of the recurrence time of the outbursts, T_C. The points are connected by a line for the outbursts that can be considered consecutive (without seasonal gaps).

3.2 The novalike systems MV Lyr and V1223 Sgr

High and low states represent a large variety of features in the optical activity of some CV types. For example, the novalike MV Lyr (e.g. [63]) spends long time intervals in the high state, with the absolute magnitude similar to the peak of the outbursts of DNe. Its occasional low states usually occur in clusters (Fig. 2a). The high-state brightness differs for various episodes, possibly because of a lower mass transfer rate to the disk in these episodes if they occur in the time segment dominated by a cluster of the low states (see also the histograms in Fig. 2b). No DN outbursts occur during the low states, which suggests that the thermal-viscous instability of the accretion disk is suppressed in novalikes. In the interpretation of [15], this can be explained by the magnetic nature of these systems (intermediate polars). The histograms of brightness in Fig. 2b show a preferred baseline level, achieved in the deep low states. In the interpretation, the disk may be almost absent and the light of MV Lyr is dominated by the WD and the donor in the low state.

The WWZ-transform (method of [6]) shows a time evolution of activity in a cluster of the low states of MV Lyr (Fig. 3). The value of WWZ indicates whether or not there is a periodic fluctuation at a given time at a given frequency. Although the transitions between the high and low states are cyclic (Fig. 3b), this cycle is unstable and is only intermittently present.

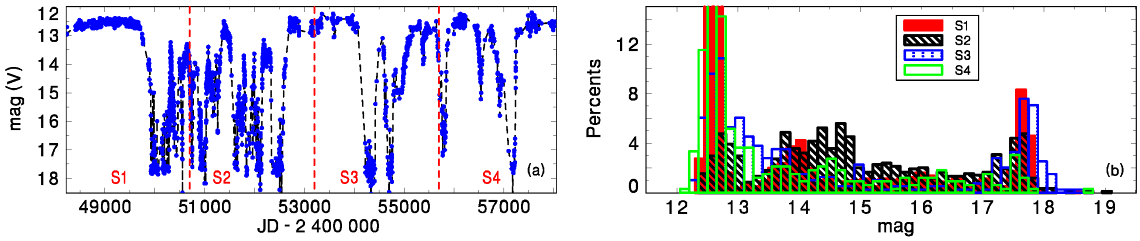

Figure 2: **(a)** Series of the high and low states of the novalike MV Lyr. AAVSO CCD data were used. **(b)** Histograms of brightness for the individual segments S1, S2, S3 and S4.

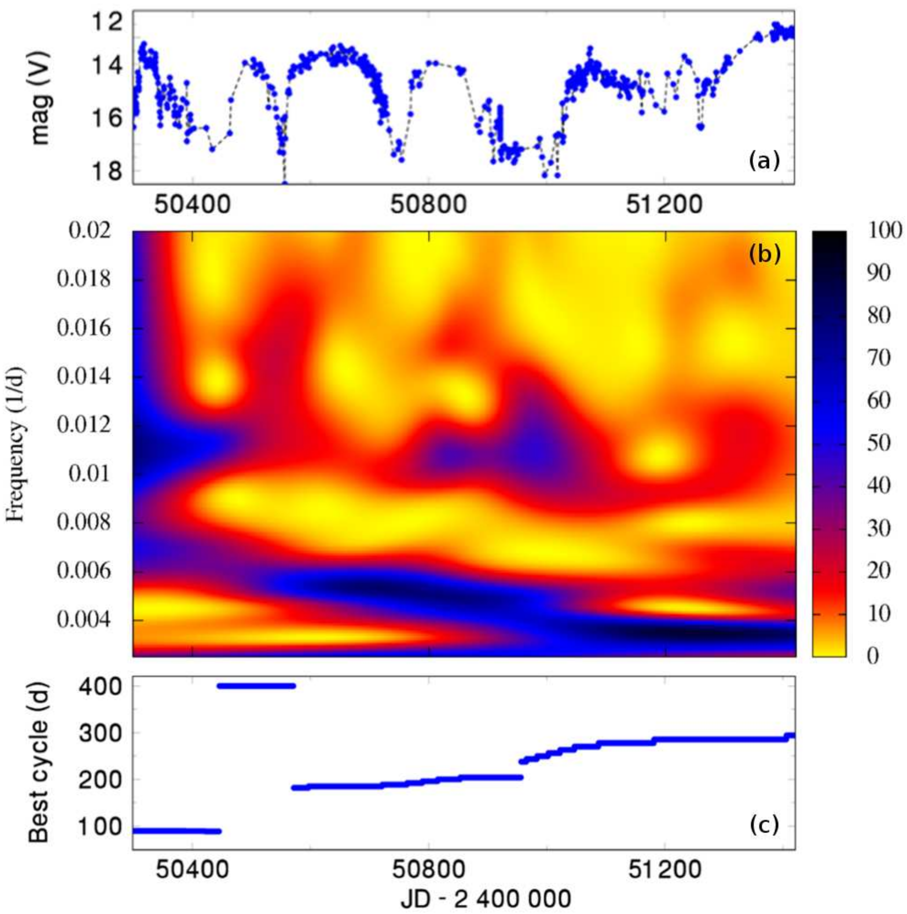

Figure 3: **(a)** Cluster of the low states of the novalike MV Lyr from Fig. 2 (AAVSO CCD data). **(b)** Cycles in the high-low state transitions (the WWZ-transform: method of [6]). Frequency is given in d^{-1}. The color scale represents the values of WWZ (see the scale). The higher the WWZ value, the better defined the cycle-length. **(c)** The best cycle-length measured in days.

V1223 Sgr is a novalike CVs as regards its long-term activity. It is also the intermediate polar because it displays rapid changes of brightness, caused by the spin modulation of the magnetized WD [54, 62, 63]. The magnetic field of this WD still allows formation of the accretion disk [1]. V1223 Sgr displays strong long-term activity corresponding to the VY Scl CVs, consisting of the dominant high states with occasional episodes of the low states. These episodes are interpreted as the decreases of the mass transfer rate from the donor (e.g. [63]). The deepest low-state episodes (deeper than 3.5 mag) of V1223 Sgr were found by [7] on photographic plates in the Harvard Plate Collection.

The histograms of brightness of V1223 Sgr are dominated by a broad bump with the peak-to-peak amplitude of more than 1 mag(B). Most low states occur in clusters. Their groups represent tails from the high state in the histograms of brightness. V1223 Sgr underwent a large change of its high/low state activity; we ascribe it to the changes of the stellar activity of the donor. The depths of the low-state episodes are largely variable, which suggests that the mass accretion onto the WD is present all the time.

According to the PDM period search (method of [55]), a series of relatively shallow (about 1 mag) low states with mutually similar depth and profile recurred with a cycle of about 3 years in V1223 Sgr in 1999–2009. In the interpretation, this cycle is driven by the changing aspect of some structure (e.g. a sequence of star spots migrating across the L1 point [28]) on the donor. Because of the differential rotation of the donor [42], this configuration cyclically influences the mass flow to the accretion disk. More details are given in [51]. This interpretation of the cycle in V1223 Sgr can be applied also to MV Lyr.

3.3 The intermediate polar EI UMa

EI UMa is the intermediate polar [37, 26] which shows significant fluctuations of the optical brightness even on the timescale of several days although its mean brightness remains roughly constant on the long timescales (several months) (Fig. 4). Several short outbursts (flares) were present only prior to JD 2 444 000 (Fig. 4a). The later observations (CRTS data, Fig. 4b) showed shallow low states but the flares were missing.

The flare is usually present only on a single plate, so it is an at most a few days long event. The field of one of these short brightenings is displayed in Fig. 5a and confirms that this flare is not caused by any artifact; notice that EI UMa is roughly as bright as the comparison star A. For comparison, EI UMa is only slightly brighter than the comparison star B in its typical brightness (Fig. 5b). EI UMa is almost absent in a short low state in Fig. 5b.

Given the absolute magnitudes (determined for the distance of 1133 ± 47 pc from [3] of the observations with the satellite *Gaia* [9] and $P_{\rm orb}$ of EI UMa, the thermal-viscous instability of the accretion disk may produce these flares because they start from the luminosity corresponding to that between outburst and quiescence of DNe determined by [63]. It is interesting that also the shallow low states in Fig. 4b occur roughly in the brightness from which also the flares are triggered. This speaks in favor of the fact that roughly the same luminosity of the disk can trigger both the flares and the shallow low states. This indicates that large changes of the mode of accretion can occur in a similar brightness of EI UMa, hence in a similar mass accretion rate onto the WD. The short

[3]http://gea.esac.esa.int/archive/

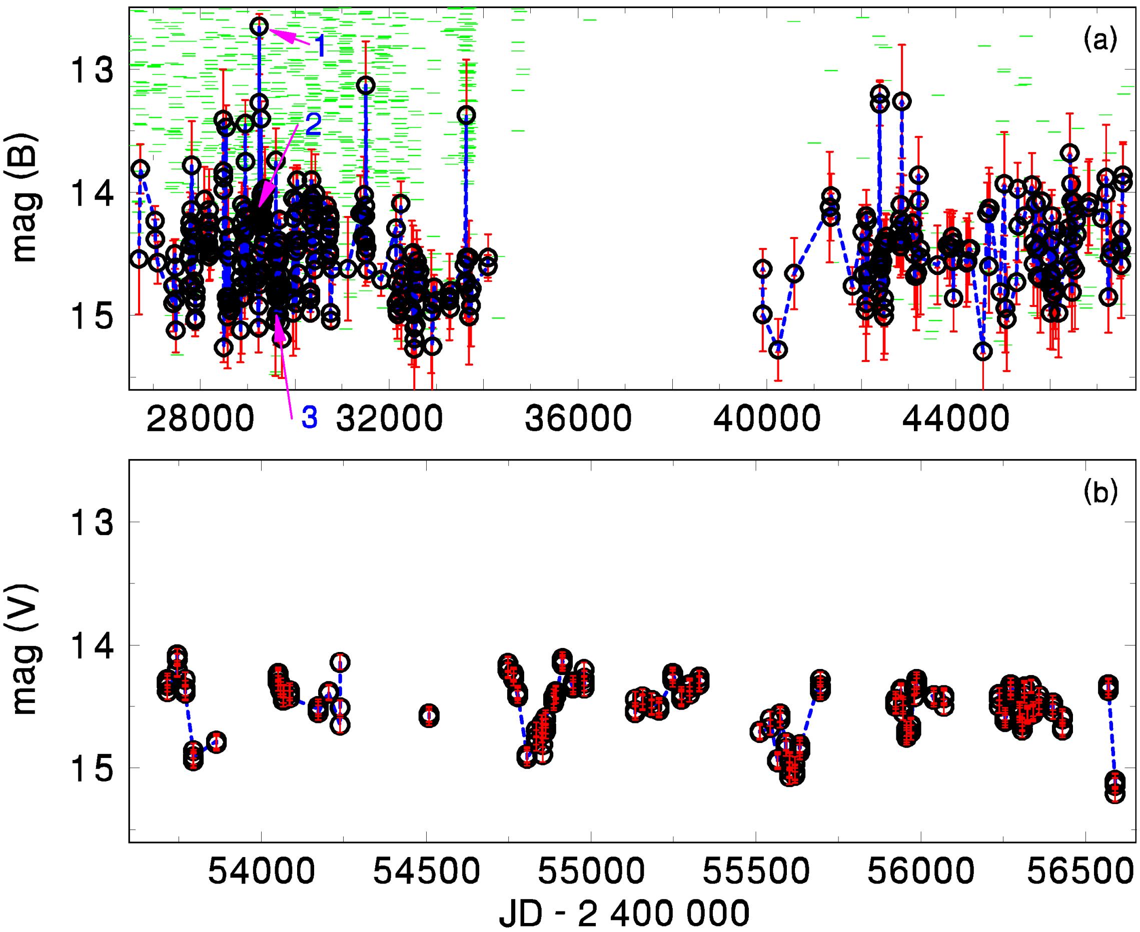

Figure 4: (a) DASCH long-term light curve (roughly the *B*-band) of the intermediate polar EI UMa. The standard deviations of brightness, listed in the original data file, are given. Short horizontal green lines represent the upper limits of brightness. The fields of the observations 1, 2, 3 are displayed in Fig. 5. **(b)** CRTS *V*-band light curve. The standard deviations of brightness, listed in the original data file, are displayed for each data point. See Sect. 3.3 for details.

duration of the flare may suggest that these brightenings come from the inner disk region set by the Alfvén radius of the magnetized WD. A modeling of such processes in the truncated disk is desirable.

3.4 V Sge – a very luminous source

V Sge with the orbital period $P_{\rm orb} = 0.514195$ d [18] is one of a very few CVs consisting of the donor considerably more massive than its accompanying WD [18, 13]. The mass transfer is therefore very high because it occurs on a thermal timescale.

V Sge displays time segments of suppressed brightness variations (called flat segments), interchanging with intervals of pronounced changes (active segments). The borderlines of the segments are sharp, several days long, while the length of the segment is several years. The character of the brightness variations in the active segments evolves (it usually consists of a series of transitions be-

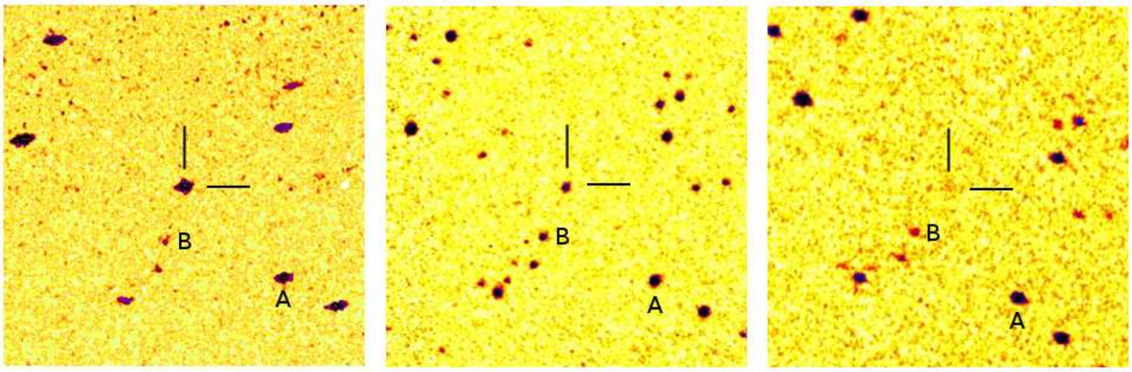

Figure 5: The field of EI UMa on the digitized DASCH plates. **(left)** Flare (JD 2 429 245.9 (point 1 in Fig. 4)). EI UMa is brighter than the comparison star A. **(middle)** A typical brightness (JD 2 429 248.8, point 2). EI UMa is only slightly brighter than the comparison star B. **(right)** A short low state (JD 2 429 612.8, point 3). EI UMa is barely detectable. It is significantly fainter than the comparison star B. North is up, East to the left. The field size is 20×20 arcmin.

tween the high and low states). These transitions are usually considerably faster than the duration of the state. The fraction of time spent in the low state gradually varied on the timescale of decades. More details can be found in [47, 48].

Even the recent revision of the distance [36] shows that the luminosity of V Sge even in the low state is still much higher than what is possible for operation of the thermal-viscous instability of the disk. Although the transitions between the high and low states are sometimes cyclic, this cycle displays a complicated evolution and is only intermittently present. In model of [13], intermittent cycles of transitions between the high and low states were interpreted as the cycles of changes of stripping of the donor by the wind from the WD.

Not only the very high absolute magnitude, but also the long-term activity (the series of the high and low states) of V Sge are similar to those of the recurrent supersoft X-ray source RX J0513–69 [38, 35].

3.5 The polars AM Her and AR UMa

AM Her, the prototype of polars (e.g. [63]), displays strong long-term activity with the high and low states.

A time-series analysis of the long-term variations of AM Her used AAVSO optical data. Rapid changes of brightness (e.g. the orbital modulation) were smoothed out by the HEC13 code, written by [16] and based on the method of [61]. This enabled to emphasize the activity on super-orbital timescale, and showed that the character of this activity changed considerably on timescales of years. The high states are not the well-defined, narrow levels of brightness. AM Her displays transitions between the high and low states with intermittently existing cycles (the time segments of at most six years). The existence of this series can be controlled by the lifetime of the active regions on the donor (e.g. starspots [28], loops [21]), which modulates the mass transfer rate. More details can be found in [52].

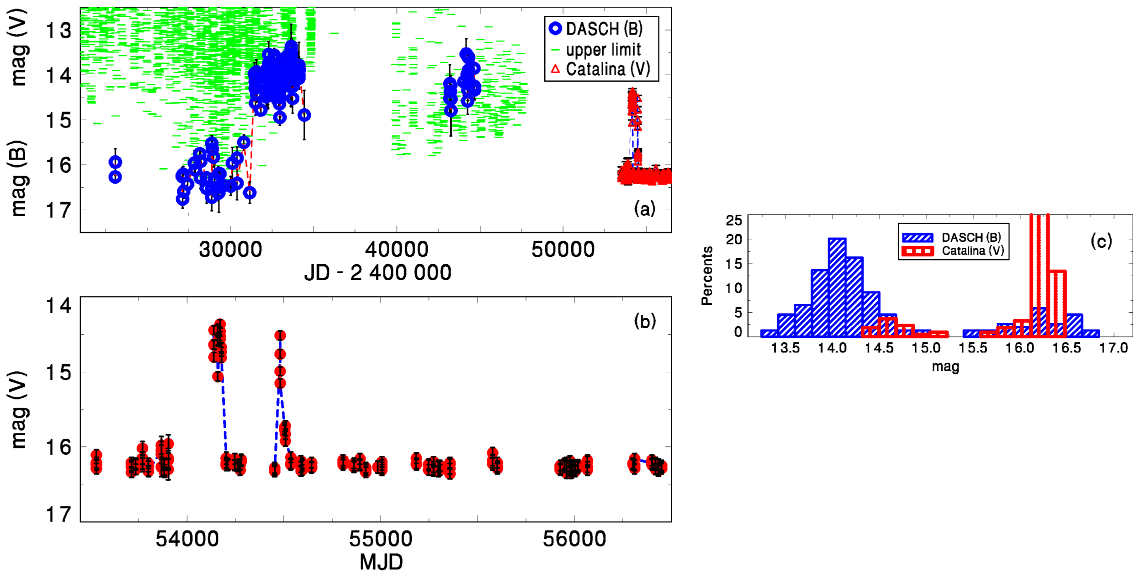

Figure 6: **(a)** Long-term light curve of the polar AR UMa. DASCH data roughly correspond to the *B*-band, CRTS data are in the *V*-band. The standard deviations of brightness, listed in the original data files, are displayed for each data point. **(b)** Detail of two short high-state episodes. **(c)** Histograms of brightness.

AR UMa is a polar containing the WD with the highest strength of the magnetic field yet detected in an accreting binary. This field plays a role in its accretion physics; dense blobs in the stream are likely fully threaded by this field from the time they leave the L1 point [45]. AR UMa is a persistent radio polar; this emission is interpreted as originating near the secondary component. Along with AM Her, it belongs to a very few persistent radio magnetic CVs [31].

The high states do not make a well-defined level of brightness of AR UMa (Fig. 6a), especially the short episodes in CRTS data occupy a faint tail of the histogram in Fig. 6c. Especially the short high states, surrounded by the long low states, in CRTS observations can hardly be explained by the appearance of the starspots at the nozzle of the donor. Isolated bursts of mass transfer from the donor are more likely. Even the long high-state episode (JD 2 431 438 – JD 2 434 447) displays a complicated structure; the occasional upper limits speak in favor of a cluster of the closely spaced high states. The orbital modulation can hardly explain the width of the high-state bump in the histogram in Fig. 6c because its peak-to-peak amplitude is usually about 0.4–0.6 mag [57, 45]. Also DASCH data folded with the ephemeris of [43] did not show any orbital modulation in the high state.

The high-state episodes (no matter how long) of AR UMa occur from a stable low-state level (Figs. 6ac). The low-state mass-transfer rate and the structure of the accretion region thus attain very similar values in these times. According to [20], the optical low state of AR UMa is dominated by beamed cyclotron radiation of the active southern accretion region with $B \leq 190$ MG.

3.6 The WD pulsar AR Sco

AR Sco contains an M5V component and a very rapidly spinning WD (1.97 min) [30]. The pulsed luminosity of AR Sco is powered by the spin-down of this highly magnetized WD while mass transfer is much less important [2]. Its P_{orb} is 3.56 hr [30] and the optical activity is dominated by a very strong orbital modulation [29]. The WD is a nearly perpendicular rotator, its open field line beams sweep the late-type companion's stellar wind. Synchrotron radiation of the shocked electrons of the wind can explain the spectral energy distribution of AR Sco [8].

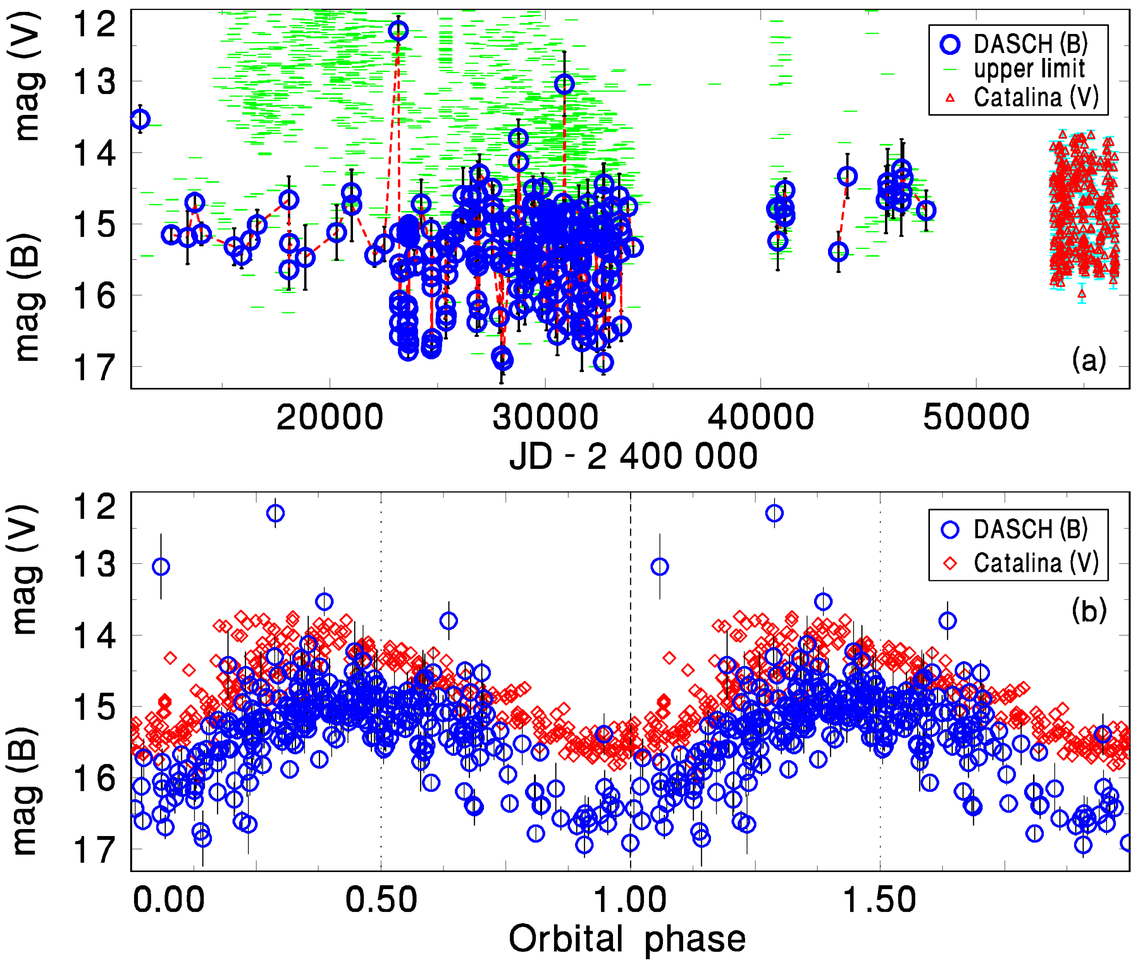

Figure 7: **(a)** Long-term light curve of AR Sco. DASCH data roughly correspond to the *B*-band. CRTS data are in the *V*-band. The standard deviations of brightness, listed in the original data file, are displayed for each data point. **(b)** The observations folded with the orbital period according to the ephemeris of [30]. Phase 0.0 corresponds to inferior conjunction of the late-type donor.

A very rapid spin of the WD (1.97 min) [30] suggests that AR Sco underwent a phase of a very high mass transfer rate. But nowadays, AR Sco resides in a very long deep low state (at least several decades), similar to that in some novalikes like MV Lyr (Sect. 3.2), but much longer.

The difference between the mean brightnesses of AR Sco in the folded DASCH and CRTS data (Fig. 7b), although these data sets are not simultaneous, can be explained by observing in the different parts of the synchrotron spectrum, modeled by [30]. The well-defined lower envelope of the modulation suggests that the mass outflow (giving rise to the synchrotron emission) from the donor does not vary largely in time and never vanished.

Persistent asymmetry of the modulation speaks in favor of a stable shape and position of the region in which synchrotron emission is produced. This stability of the modulation also speaks against precession of the axis of the magnetic poles, at least on the timescale shorter than or comparable to about a century (this constrains the possible explanation of [25]).

However, some phases of the modulation undergo variations in time. [29] found the changes of the orbital modulation in the surroundings of phase 0.3. A comparison of the DASCH light curve in Fig. 7b with CRTS data or the observations of [29] suggests either a stable modulation in the time covered by DASCH data but different in the phase 0.3 and less steep between phases 0.3 and 0.6 in the later time, or a more complicated spectral energy distribution of synchrotron emission.

Several remarkably bright points (irrespective of the orbital phase) in Fig. 7b can be explained as the large (but short) bursts of matter from the system. These bursts are very rare all the time because any strong clusters would preclude the orbital modulation of AR Sco. They may be analogous to the flares in another propeller, AE Aqr, whose thermal flares are interpreted as arising from collisions between the high-density regions in the material expelled from the system after interaction with the rotating magnetosphere of the WD [33].

3.7 Role of classical nova outbursts

X Ser which erupted as a classical nova in 1903 [4, 5] can serve as an example of influence of such outbursts on the long-term activity of CVs.

This post-nova displays a strong complex activity with the characteristics of various CV types. Both novalike and DN features are present. In the interpretation, X Ser rapidly transitioned to the thermal-viscous instability regime of the disk, initially only intermittently. The occurrence of the DN outbursts shortly after the end of the nova outburst suggests that the mass transfer rate into the accretion disk was usually not sufficiently high to prevent the thermal-viscous instability of X Ser. A high-state episode suggesting an ionized disk several decades after the nova can be ascribed to a burst of mass from the donor. The very long $P_{\rm orb}$ of 1.478 d was determined from the radial velocities [59]. This value is rare for a CV, and hence large accretion disk of X Ser can contribute to this disk instability shortly after the nova outburst. More details can be found in [53].

4. Conclusions

Discrete features dominate the long-term light curves of most CV types. Small changes of $T_{\rm C}$ of the DN outbursts in a given CV (see also [60]) suggest that the individual outbursts depend on each other. This can be explained if only a small fraction of the disk matter is accreted in a given outburst. A large role of the processes in the cool disk (between the outbursts) plays a big role.

The low states in novalikes and polars often occur in clusters. This can produce a long cycle (thousands of days) in the state transitions. In the interpretations, changes of the position of the active regions on the donor (loops [21]), starspots [28]) with respect to the L1 point by a differential rotation of the donor [42] are suggested. The short high states, surrounded by the long low states, can be explained by isolated bursts of mass transfer from the donor. A variable stripping of the donor by a very strong wind from the WD in very luminous CVs (V Sge) [13] can be involved.

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The brightness of some intermediate polars can largely fluctuate on the timescale of days and also produce intense flares. The short duration of the flare may suggest a role of the Alfvén radius of the magnetized WD.

The magnetic field of the WD of the propellers, with the luminosities similar to the low states of novalikes, can strongly influence the optical emission by flares and synchrotron emission. This depends on the configuration of this field.

Large changes of the type of activity occur during the decades after the classical nova outburst. Several processes are the promising explanations: the inner disk region remaining in the ionized state due to irradiation by the hot WD while the thermal-viscous instability already occurs in the outer disk region [44], bursts of mass transfer from the irradiated donor [19], strong orbital modulation of the irradiated side of the donor [32].

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DISCUSSION

PAUL MASON: The sharp peaks seen at the faint end in the histograms of AM Her and AR UMa do indicate the true low state. However, the high states have broad histograms. Have you considered folding the high state data with phase in order to study the variations between different high states after removing orbital variability?

VOJTĚCH ŠIMON: The light curve of AM Her and its histograms were already corrected for the orbital modulation by smoothing. The broad peaks of the high states in these histograms thus show that the individual high states have significantly different brightnesses. Folding of the high-state DASCH data of AR UMa with the orbital period showed only a scatter without the orbital modulation. The histogram of brightness is thus dominated by the superorbital changes.