Flickering around the outburst cycle in Kepler dwarf novae

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ABSTRACT
Taking advantage of the unparallel quantity and quality of high cadence Kepler light curves of several dwarf novae, the strength of the flickering and the high frequency spectral index of their power spectra are investigated as a function of magnitude around the outburst cycle of these systems. Previous work suggesting that the flickering strength (on a magnitude scale) is practically constant above a given brightness threshold and only rises at fainter magnitudes is confirmed for most of the investigated systems. As a new feature, a hysteresis in the flickering strength is seen in the sense that at the same magnitude level flickering is stronger during decline from outburst than during the rise. A similar hysteresis is also seen in the spectral index. In both cases, it can qualitatively be explained under plausible assumptions within the DIM model for dwarf nova outbursts.

Key words: stars: activity – (stars:) binaries: close – (stars:) novae, cataclysmic variables – stars: individual: V1504 Cyg, V344 Lyr, V447 Lyr, V516 Lyr, KIC 9202990

1 INTRODUCTION
The phenomenon of flickering is ubiquitous in astronomical systems where accretion of matter onto a central object occurs. In the optical regime it is most conspicuous in cataclysmic variables (CVs) where it manifests itself as a continuous series of apparently stochastic overlapping flares which – depending on the particular system and photometric state – can reach full amplitudes between some tens of milli-magnitudes up to more than an entire magnitude. In spite of an increasing number of specific studies in recent years, flickering is still one of the lesser understood properties of CVs. For a review about the state of the art in this field see the introduction to Bruch (2015).

CVs are close binary stars with orbital periods between ≈80 min and rarely more than about 10 hours, where a late type companion – the secondary –, which is in most cases on or close to the main sequence, fills its Roche lobe and transfers matter to a white dwarf primary. In the absence of strong magnetic fields conservation of angular momentum forces this material to form an accretion disk around the white dwarf where viscous forces cause it to slowly move inwards and to finally settle on the surface of the compact star. In optical light this disk is almost always the most luminous part of the system. For a comprehensive description of most aspects of CVs, see, e.g., Warner (1995).

The most common of the many subtypes of CVs are the dwarf novae. They are characterized by semi-regularly spaced outbursts with amplitudes ranging from roughly 2 – 8 mag, occurring at intervals which may be as short as a couple of days in some systems and as long as decades in others. They last a few days to rarely more than two weeks. In general, the dichotomy between quiescent states and outbursts is explained by a thermal instability which develops in the accretion disk (Smak 1971; Osaki 1974; Lasota 2001). In short, during quiescence the disk is in a low viscosity state such that less matter is accreted onto the surface of the white dwarf than is transferred from the secondary. Consequently, the column density (and the temperature) of the disk increases, until a thermal instability caused by the ionization of hydrogen sets in, resulting in an increase of the viscosity and thus an increased dumping of matter onto the central object. The corresponding release of potential energy manifests itself as an outburst. After most of the transferred matter is drained from the accretion disk the system returns to the quiescent state and the cycle starts anew.

The non-trivial problem to quantify the strength of the flickering (or the flux of the flickering light source relative to the total light of the system) in an objective way, enabling a comparison between different systems and photometric states, has recently been addressed by Bruch (2021) (hereafter referred to as B21). He parameterized the flickering strength, expressed in magnitudes, by the full width at half maximum (FWHM) of a Gaussian fit to the distribution of data points in a flickering light curve, after applying corrections for various systematic effects (see below for details). B21 called this quantity $A_{60}$, the number 60 indicating that it only refers to flickering occurring on times scales below 60 min. He measured $A_{60}$ in several thousand light curves of more than 100 CVs.

Another – and more often applied – approach to quantify the properties of flickering is based on a frequency analysis, i.e., the study of the power spectra of CV light curves (e.g., Dobrokta et al. 2010, 2012, 2014, 2017; Kraicheva et al. 1999; Scaringi et al., 2012). Most of these efforts concentrate on the indentification and characterization of break points in the power spectra in a double logarithmic
representation, and less on their slope (spectral index) at high frequencies.

The flickering amplitude in dwarf novae is observed to depend on the outburst state. It has long been known that flickering is much stronger during quiescence than during outbursts. But this has never been quantified before B21 systematically studied the evolution of the flickering strength around the dwarf nova outburst cycle. He found that, expressed in magnitudes, flickering in dwarf nova has the tendency to remain constant whenever the system is brighter than a threshold magnitude level which is approximately half way between quiescence and outburst maximum. Only below this level the amplitude rises rapidly with decreasing system brightness. This means that on the flux scale the brightness of the flickering light source is proportional to the total flux above the threshold, while its contribution to the total light increases when the system is fainter. Concerning the frequency behaviour, the dependence of the spectral index around the outburst state has never been studied.

The data used by B21 came from multiple terrestrial observatories. Their quality and suitability for flickering studies are rather inhomogeneous. The above mentioned various corrections necessary to render the flickering strength measured in different light curves comparable to each other are frequently not known to a high precision and thus introduce uncertainties. Observations with sufficient time resolution around the outburst cycle of dwarf novae are most often quite fragmentary. Power spectra of individual light curves are in general rather noisy. All this makes it difficult to follow the evolution of the flickering strength and the spectral index around the outburst cycle of individual dwarf novae. This would only be different if high quality data sets covering various cycles were available.

Such data indeed exist for a few systems. Among the many stars observed by the Kepler space mission (Koch et al. 2010) five dwarf novae were observed in short cadence mode for up to almost four years, in some cases with only small interruptions. This means that homogeneous light curves, continuous over long time intervals, with a time resolution of ≈59 s are available, covering numerous outbursts and quiescent phases. These data are used here to investigate the evolution of the flickering strength and of the spectral index from quiescence to outburst and back again.

2 THE TARGET STARS
The dwarf novae for which Kepler short cadence data are available are V1504 Cyg, V344 Lyr, V447 Lyr, V516 Lyr and KIC 9202990. For some of these targets, long cadence observations (time resolution: ≈29 min) are also available. They are, however, not useful in the present context because they cannot resolve the flickering activity and are thus ignored.

Both, V1504 Cyg and V344 Lyr are short period dwarf novae of the SU UMa subtype. This means, that apart from normal outbursts they occasionally exhibit superoutbursts which are significantly longer and brighter than normal ones. These systems were discovered by Beljawski (1936) and Hoffmeister (1966), respectively. Their Kepler data have repeatedly been analysed in the literature, often in the same publication. These concentrate on studies of the outburst behaviour and of (positive and negative) superhumps.

(Still et al. 2010; Wood et al. 2011; Cannizzo et al. 2012; Osaki & Kato 2013a,b, 2014). The investigation of the flickering behaviour in these stars is restricted to an analysis of the frequency spectrum by Dobrotka & Ness (2015) and Dobrotka et al. (2016).

Compared to V1504 Cyg and V344 Lyr, much less is known about the other dwarf novae regarded here. Except for KIC 9202990 they are also significantly fainter which turns the secure measurement of their flickering properties more difficult, in particular in quiescence.
V447 Lyr was discovered as a variable star by Ramsay et al. (1992) who combined optical spectroscopy with Kepler light curves. V447 Lyr is eclipsing at a period of 0.1556270 d. Individual eclipses can only be securely identified during outburst, while in quiescence they are drowned in noise. No further periods were detected in the Kepler data. V447 Lyr exhibits long and short outbursts. It is remarkable that in all long outbursts the initial rise is followed by a small decline before the final rise to maximum. As was pointed out by Ramsay et al. (2012) this resembles very much the structure of superoutbursts in SU UMa stars which are often triggered by a normal outburst.

KIC 9202990 is unusual in the sense that its Kepler light curve is characterized by a continuous series of low amplitude modulations repeating on the time scale of two weeks (Ostensen et al. 2010). Superposed is a shorter stable period of ≈4 h. Ramsay et al. (2016) discuss these observations in more detail and interpret the longer (quasi-) periodicity as stunted outbursts as sometimes seen in dwarf novae (but never as the continuous series seen in KIC9202990). The 4 h period is considered to be orbital.

3 THE DATA

All data used in this study were retrieved from the Barbara A. Mikulski Archive for Space Telescopes (MAST)\(^1\). Among the various formats in which they are available I chose the SAP (Simple Aperture Photometry) flux data\(^2\) restricting myself to data obtained in short cadence mode. Some among the millions of data points were identified to deviate strongly from neighbouring points in the light curves (more so for the fainter objects than for the brighter ones). These must be considered erroneous. Consequently they have been removed. The SAP flux of V516 Lyr in the first two monthly Keper data sets (BJD 2455568-636) is systematically lower (by about 1.3 mag in quiescence) than in all other data sets. They have therefore been ignored.

The long term Kepler light curves which have never been shown in their entirety are reproduced in Figs. 1 - 5 which are organized such that each panel contains a 200 day section.

4 THE STRENGTH OF THE FlickERING

Flickering manifests itself as an (at least apparently) stochastic process. The problem of how to measure its strength has been addressed in detail by B21. Here, I follow the prescriptions outlined in that publication. As already briefly mentioned in Sect. 1, the flickering strength is parameterized by the FWHM \(A_{60}\) of a Gaussian fit to the distribution of data points in a flickering light curve (expressed in magnitudes)

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\(^1\) https://mast.stsci.edu/portal/Mashub/clients/MAST/Portal.html

\(^2\) SAP data are preferred here over PDC-SAP (Presearch Data Conditioning Module Simple Aperture Photometry fluxes) data because the latter contain intervals with an anomalous flickering behaviour (e.g., BJD 2455415-31 in V344 Lyr) which is not observed in the SAP flux data. These intervals invariably coincide with monthly datasets which contain a superoutburst and end with the beginning of the next dataset. It is therefore close at hand to suspect that the unusual flickering is an artefact of data reduction.

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V516 Cyg is another SU UMa type dwarf nova. It was discovered as a variable star by Kahužny & Udalski (1992) and confirmed as a cataclysmic variable by Kalužny et al. (1997). A detailed study based on Kepler data was performed by Kato & Osaki (2013) who studied mainly the outburst behaviour. They draw attention to the occasional presence of double outbursts.

V447 Lyr was discovered as a variable star by Romano (1972). Its orbital period lies above the range of periods of SU UMa stars. The only detailed study of this system was published by Ramsay et al. (2012) who combined optical spectroscopy with Kepler light curves. V447 Lyr is eclipsing at a period of 0.1556270 d. Individual eclipses can only be securely identified during outburst, while in quiescence they are drowned in noise. No further periods were detected in the Kepler data. V447 Lyr exhibits long and short outbursts. It is remarkable that in all long outbursts the initial rise is followed by a small decline before the final rise to maximum. As was pointed out by Ramsay et al. (2012) this resembles very much the structure of superoutbursts in SU UMa stars which are often triggered by a normal outburst.

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from which variations on time scales longer than the typical flickering time scales (here chosen to be 60 min) have been subtracted. In order to render this quantity comparable for different systems and photometric states, some conditions have to be met and several corrections have to be applied as listed in Sect. 2 of B21. Due to the homogeneous characteristics of the Kepler data, the latter are either much easier to quantify than in more inhomogeneous data typical for terrestrial observations, or can even be ignored.

In order to follow the variations of the flickering strength around the outburst cycle of the dwarf novae their Kepler light curves of are cut into sections of 8 hours (about the upper limit of a long light curves observable in terrestrial observations). This is long enough for the flickering in each section to meet the requirement to be representative.

The second requirement, i.e., separating variations unrelated to flickering, is met by subtracting a Savitzky & Golay (1964) filtered light curve with a cut-off time scale of 60 min from the original one. This effectively removes orbital variations as well as modulations on longer time scales. Thus, only flickering occurring on times scales of less than 60 min are regarded (as has been done by B21). It turned out that this procedure could sometimes not remove satisfactorily the pointed maxima of superhump variations occurring during the supermaxima of the SU UMa stars. Therefore, supermaxima (and subsequent time intervals with persisting superhumps identified in power spectra of the data in these intervals) were disregarded.

A correction for data noise, difficult in the general case because the noise level is often not well known, is easy here because the original Kepler data files provide the flux error for each data point of the light curve. This is used to correct the measured FWHM of the data distribution function for the effect of noise.

A reduction of $A_{60}$ to a standard time resolution of the data (and thus correcting for the effect that a finite integration time always acts as a filter, reducing the difference between local minima and maxima in a flickering light curve) is only required if the flickering in light curves obtained using different integration times is to be compared. However, the Kepler short cadence data were all observed with the same time resolution, rendering a corresponding correction unnecessary.

Applying a correction for the contribution of the secondary star is not necessary for the SU UMa stars of the current sample because that contribution is negligible in short period cataclysmic variables. This may be different for V447 Lyr and KIC 9202990 which have longer orbital periods. No quantitative information for the secondary star contribution in these systems is available. However, since no comparison of their flickering strength with that in other CVs will be performed, neglecting a corresponding correction does not invalidate the present results.

Fig. 6 shows the results for four of the five dwarf novae studied here. In all cases the small black dots represent $A_{60}$ measured in the individual 8 h sections of the light curve, plotted against the average magnitude of all data points in that section. It turned out that excessive noise in the fainter systems V447 Lyr and V516 Lyr (but also to some extend in V344 Lyr) inhibited to measure $A_{60}$ in some sections which were thus ignored. The magnitude scale is arbitrary and has been chosen such that the zero point corresponds to the brightest average magnitude in any of the light curve sections (and thus to the brightest maximum) of each dwarf nova. The coloured dots are average values of $A_{60}$, binned in intervals of $\Delta m = 0.1$. The blue ones refer to $A_{60}$ measured in sections before outburst maxima (from quiescence halfway between a given outburst maximum and the preceding one), the red ones after outburst (from outburst maximum to quiescence halfway to the next outburst). The error bars (mostly smaller than the plot symbols for V1504 Cyg) represent the standard error of the mean.

Two interesting features can be seen in the results. The quality of the data of B21 permitted him to see only on the average over several systems that flickering remains constant on the magnitude scale whenever a dwarf nova system remains above a certain brightness level during the outburst cycle and starts to grow only when it is closer to quiescence. Here, this is confirmed in individual systems in at least two of the four investigated cases. In V344 Lyr $A_{60}$ is quite constant as long as the system is less than $\approx$1-2 mag below maximum [more so before maximum (blue dots) than afterwards (red dots)]. Thereafter, first a gradual and then a faster rise sets in. In V447 Lyr the $A_{60} - \Delta m$ relationship remains absolutely flat up to 1.5 mag below maximum before a gradual rise begins. The case of V516 Lyr is less clear. But disregarding the lone point close to $\Delta m = 0$, the distribution of data points appears also to be compatible with a constant close to outburst maximum. In contrast, V1504 Cyg does not show such a plateau phase, but $A_{60}$ continually drops as the star gets brighter. However, even in this case a change in slope occurs close to $\Delta m \approx 1.9$ as becomes obvious when the average difference in $A_{60}$ between neighbouring datapoints is regarded.

While this behaviour thus confirms the results of B21, the second feature revealed here has never been seen before. Most clearly in V1504 Cyg, but also in V344 Lyr there is a hysteresis in the flickering strength around the outburst cycle. On the rise to outburst (blue dots in Fig. 6) $A_{60}$ is systematically smaller at a given magnitude than on the decline (red dots). This is not seen in V447 Lyr and V516 Lyr, either because the hysteresis is really absent, or because the inferior quality of the respective light curves inhibits its detection.

In the unusual system KIC 9202990 the flickering strength behaves differently (Fig. 7). Over the quite limited range of variability flickering remains on a approximately constant low level of $A_{60} = 0.0074 \pm 0.0016$ mag with possibly a slight increase during the minima as well as the maxima of the outburst cycle. There may be a slight decrease of $A_{60}$ during the exceptionally faint minima ($\Delta m > 0.75$) observed in the interval JD 2456320–50 (see Fig. 5). But statistics are very poor in this magnitude range.

In their investigation of flickering in the Kepler data of V1504 Cyg Dobrotka & Ness (2015), among other aspects, study the dependence of the scatter of the data in small time intervals as a function of flux during quiescence and outburst maximum. This can be considered as a proxy of the flickering strength. This relation is normally referred to as the rms-flux relation. This denomination is, however, misleading because

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For the record: In order to reduce the flickering strength to the standard time resolution of 5 s defined by B21 the measured and noise corrected FWHM should be divided by 0.85.
it does not relate the rms (root mean square), but the standard deviation of the sample of considered data points to the flux (see the definition of $\sigma_{\text{rms}}$ according to eq. 1 of Dobrotka & Ness 2015). Adopting the established, although erroneous, nomenclature this definition renders the rms as a measure of the flickering strength conceptually quite similar to $A_{60}$ as defined by B21. In both cases, the distribution of data points in a light curve interval is regarded. In fact, calculating $\sigma_{\text{rms}}$ for V1504 Cyg and V344 Lyr [using intervals comprising 10 data points as has been done by Dobrotka & Ness (2015)], multiplying the results by the ratio between the standard deviation and the full width at half maximum of a Gaussian to account for the different definitions of $\sigma_{\text{rms}}$ and $A_{60}$, and transforming fluxes into magnitudes yields a relation just as shown in Fig. 6.

The corresponding relations on the flux scale are shown in Fig. 8 [using different resolutions for the low (left) and high (right) flux regimes for better visualization]. For V1504 Cyg, the results of Dobrotka & Ness (2015) are recovered, most importantly the linear $\sigma_{\text{rms}}$ – flux relation during quiescence which does not extend to outburst phases. However, at low fluxes [not covered by Dobrotka & Ness (2015)] a significant steepening is observed. In V344 Lyr, a linear $\sigma_{\text{rms}}$ – flux relation is present at most over a quite limited flux range. One reason may be the dominance of noise in the low flux regime which causes a flattening of the relation. The slight hump at intermediate fluxes (best seen in V344 Lyr between 2000 and 4000 SAP flux units) is not due to flickering but reflects an increased standard deviation of the data points in particular during the steep rise to maximum because of a significant increase in brightness even over the short time scale comprised by the 10 contributing data points. At high fluxes, the rise of $\sigma_{\text{rms}}$ is steeper in V344 Lyr than in V1504 Cyg, reflecting the better expressed constant phase of the flickering strength on the magnitude scale until well below maximum in V344 Lyr as compared to V1504 Cyg (see Fig. 6).

A distinctive feature in the rms-flux relation of V344 Lyr is a hump centred on 500 SAP flux units which interrupts the otherwise almost flat relation above the upper end of the linear rms-flux rise. A similar structure was also observed by Dobrotka et al. (2016) (their Fig. 2) who interpreted the rising part of the hump as a continuation of the linear rms-flux relation observed at lower levels and explain the delay by the contribution of non-flickering flux provided by the light source of a negative superhump. Considering that
the intervals with positive superhump have been excluded from the present study (Sect. 4), that no similar structure is seen in the case of V1504 Cyg, and that negative superhumps only persist for limited time intervals in V344 Lyr and V1504 Cyg (Osaki & Kato 2014), it is questionable if superhumps can cause such a prominent feature in the rms-flux curve of V344 Lyr based on data comprising predominantly intervals without superhumps. The flux level of $\approx 500$ SAI units in V344 Lyr already corresponds to the early rise to and the late decline from outbursts. The hump may therefore be related to changing flickering properties during either or both of these transition phases.

5 THE SPECTRAL INDEX OF THE FLICKERING

Since the pioneering studies of Elsworth & James (1982, 1986) it is well known that at high frequencies flickering manifests itself as red noise in the power spectra of cataclysmic variable light curves, meaning that $P \propto f^{-\gamma}$, where $P$ is the power, $f$ the frequency and $\gamma$ the spectral index. At very high frequencies white noise due to (approximately) Gaussian measurement errors takes over. On the double logarithmic scale, red noise causes a linear drop of the power with increasing frequency with a slope of $-\gamma$, and white noise results in a constant power level. Here, I will investigate if and in which way $\gamma$ changes over the dwarf nova outburst cycle.

As in the case of the flickering strength, care must be taken to avoid that variations on longer time scales introduce a bias. This holds true particularly during the rise and decline phases of the outbursts. Even if long time scales correspond to low frequencies such variations have a significant bearing also on the high frequency part of the power spectra. This can be seen in Fig. 9 where the black dots represent the double logarithmic power spectrum (Lomb-Scargle periodogram (Lomb 1977; Scargle 1982), using the normalization of Horne & Baliunas (1986) binned in intervals of $0.05 \log(f)$ (where $f$ is the frequencies expressed in cycles/day), of a particularly long ($\approx 15$ days) quiescent phase of V1504 Cyg. It exhibits excellently the exponential drop of power towards high frequencies up to the Nyquist frequency, as is shown by the black solid line which is a least squares fit to the data points above $f = 20$ d$^{-1}$ (thus avoiding lower frequencies which may be influenced by orbital variations; see below). The red dots represent the power spectrum of the same data, after a gradient typical of the outburst decline phase of V1504 Cyg has been added. This additional slope in the data changes the power spectrum in two ways: The spectral index becomes steeper, and some wiggles appear at high frequencies. The impact of the gradient should be even larger if typical values for the much steeper rise to outburst maximum were adopted.

Both effects can be avoided by subtracting a filtered version from the light curve (including the gradient). Using for this purpose a Savitzky-Golay filter with a cut-off time scale of 60 min as used to measure the flickering strength results in the power spectrum represented by the blue dots in the figure. Now, the power at low frequencies is strongly reduced, but at high frequencies it follows very well the power spectrum of the original data. However, the turn-over is at frequencies well above 20 d$^{-1}$, reducing significantly the frequency range suitable to measure $\gamma$. This unduly reduces the precision of $\gamma$ in particular when smaller light curve sections (fewer data) are contemplated and when white noise does not permit to use all frequencies up to the Nyquist limit to measure $\gamma$. Choosing 8 hours for the filter cut-off time scale (i.e., the time base of the light curve sections used to measure the flickering strength) results in the green dots in Fig. 9. They also follow excellently the power spectrum of the original data over the entire frequency range suitable to measure $\gamma$. I restrict the frequency analysis to V1504 Cyg, V344 Lyr and KIC 9202990, because the data of V447 Lyr and V516 Lyr are so noisy that white noise already dominates the power spectra at comparatively low frequencies. I first regard the average (double logarithmic) power spectrum of the three stars (Fig. 10), based only on the quiescent phases of V1504 Cyg and V344 Lyr (the continuous small amplitude variations of KIC 9202990 do not warrant to make a distinction between quiescence and outburst in this system).

In all cases the orbital periods and their first harmonics manifest themselves as well expressed peaks in the power spectra (marked by arrows in Fig. 10). Avoiding these frequency ranges, the spectral index is measured in the intervals delimited by the broken vertical lines. The power spectrum of KIC 9202990 is declining very much linearly.
V344 Lyr has a much smaller spectral index and – being slightly steeper spectral index, the average power spectrum of V1504 Cyg shows a slight deviation from linearity (i.e., a small shoulder close to \(\log(f)\)). The latter is thus avoided when measuring the spectral index, as it is based on very few data points. Long term changes of \(\gamma\) over time (lower left frame of Fig. 11) are not noticeable beyond small wiggles.

In contrast to V1504 Cyg, V344 Lyr, although much noisier, appears to exhibit a slight increase of \(\gamma\) as the system approaches outburst maximum. A marginal increase of \(\gamma\) during decline is observed just below \(\Delta m = 2.8\). If real, this coincides with the magnitude range where a slight hysteresis in the flickering amplitude is seen in this system. As a function of time, \(\gamma\) exhibit a small but systematic long term decrease.

The amplitude of the variations of KIC 9202990 is much smaller than that of the other two systems (the exceptionally low minima in the interval JD 2456320–50 have been ignored). Similarly to the behaviour of the flickering strength, there appears to be an upward turn of \(\gamma\) close to the minimum and – less clear – close to the maximum of the mini-outbursts. No significant difference of the behaviour before and after the outbursts is observed. Concerning the long-term evolution, a slight decrease of \(\gamma\) is observed in the last of the three distinct intervals (Fig. 5) during which KIC 9202990 was observed.

6 DISCUSSION

The hysteresis of the flickering amplitude around the outburst cycle in V1504 Cyg and V344 Lyr, the amplitude being smaller during the rise to outburst than during decline, has never before been noticed in these or in any other system. This attests to the unparallel quality and quantity of the Kepler data for the purpose of the current study. At the same time it calls for an explanation.

Considering the disk instability model (DIM) for dwarf novae outbursts (e.g., Lasota 2001), the mere existence of a hysteresis can qualitatively be explained in a scenario where the flickering part of the flux of the accretion disk is a constant fraction of the locally emitted flux, but this fraction

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\gamma \text{(qui.)} = 1.52 \\
\gamma \text{(outb.)} = 1.35 \\
\gamma \text{(entire light curve)} = 1.31
\]

above \(\log(f) = 1.2\) up to the Nyquist frequency. With a slightly steeper spectral index, the average power spectrum of V1504 Cyg shows a slight deviation from linearity (i.e., a small shoulder close to \(\log(f) = 2.5\)) and an indication of a turn-over to white noise close to the Nyquist frequency. The latter is thus avoided when measuring the spectral index, while the former – too small to be visible in the spectra of individual light curve sections used to determine the evolution of \(\gamma\) around the outburst cycle (see below) – is ignored. V344 Lyr has a much smaller spectral index and – being fainter – white noise clearly takes over at high frequencies, limiting thus the useful interval to measure the spectral index. \(\gamma\), as measured in the average power spectra, is listed in Table 2, separately for quiescent and outburst phases.

In order to study variations of \(\gamma\) around the outburst cycle, Lomb-Scargle periodograms of the same light curve sections defined in Sect. 4 were calculated after subtraction of variations on time scales longer than 8 h. \(\gamma\) was then measured as the slope of a linear least squares fit to the frequency intervals quoted in Table 2 of the periodograms in double logarithmic representation, binned in intervals of \(\Delta \log(f) = 0.05\). The results are shown in Fig. 11 where \(\gamma\) is plotted as a function of the magnitude (using the same magnitude scale as in Sect. 4) in the upper frames and against time in the lower ones. To facilitate a comparison, the \(y\)-axis scale of the diagrams is the same for the different systems. The blue (before maximum) and red (after maximum) dots in the upper graphs represent the average values of \(\gamma\) in magnitude intervals of \(\Delta m = 0.2\) (0.05 for KIC 9202990). The error bars (often smaller than the plot symbols) indicate the standard error of the mean. In the lower frames, the red graphs connect the average values of \(\gamma\) in time intervals of 25 days.

For individual light curve sections the periodograms are not well enough defined to measure \(\gamma\) with high precision. Thus the scatter is considerable, in particular for the fainter star V344 Lyr. But the ensemble of all individual values yields a systematic behaviour which, however, is different for the three systems.

V1504 Cyg is the most interesting case. No significant evolution of \(\gamma\) occurs before and on the rise to outburst maximum. But during the decline from outburst a significant increase is evident at intermediate magnitudes. This is reminiscent of the hysteresis observed in the flickering amplitude of the same system (as is the case in Fig. 6 the downward turn at the faint end of the red curve is not considered significant as it is based on very few data points). Long term changes of \(\gamma\) over time (lower left frame of Fig. 11) are not noticeable beyond small wiggles.

Table 1. Spectral index \(\gamma\) measured in average power spectra of V1504 Cyg, V344 Lyr during quiescence and outburst and KIC 9202990 (all data combined), together with the frequency range used to measure \(\gamma\).

| Object       | frequency range (d\(^{-1}\)) | \(\gamma\) (qui.) | \(\gamma\) (outb.) |
|--------------|-------------------------------|------------------|------------------|
| V1504 Cyg    | 35.5 . . . 631                | 1.52             | 1.35             |
| V344 Lyr     | 50.1 . . . 200                | 0.49             | 0.84             |
| KIC 9202990  | 15.8 . . . 725                | 1.31             | 1.31             |

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\log(f) = 1.2
\]
being higher/lower for those parts of the disk which are on the lower/upper branch of the famous S-shaped relation between the surface column density and the effective temperature. On the upper branch, the disk can be approximated by a standard steady state accretion disk (Shakura & Sunyaev 1971), and the local temperature and thus the emitted flux is proportional to the local mass transfer rate and decreases strongly with increasing radius in the disk. The quiescent disk, on the other hand, is generally observed to have a much smaller radial temperature gradient (e.g., Wood et al. 1992; Vrielmann et al. 2002; Baptista & Bortoletto 2004). Thus, during quiescence the surface brightness of the disk is not such a strong function of the distance from the central star and therefore the outer parts provide more flux to the total light compared to the inner parts than is the case during outburst maximum. The observed shape of the outburst light curves of the currently discussed systems (steepest rise and more gradual decline) is normally interpreted such that a heating front starts in the outer disk and then propagates inwards, followed by a cooling front propagating in the same direction (e.g. Smak 1984; Cannizzo et al. 1986, for the specific case of V1504 Cyg and V344 Lyr see also Osaki & Kato (2013a) and Cannizzo et al. (2010)). At a given magnitude on the rise to the outburst the observed flickering is a mixture of the flickering of the remaining quiescent inner part of the disk and the lower flickering of the outer parts which are already in outburst. At the same magnitude on the decline the situation is inverted. Since, however, the relative flux contribution of outer parts of a quiescent disk, as compared to the inner disk, is higher than in an outbursting disk, stronger flickering is now seen. Thus, a hysteresis arises.

In order to quantify this effect full DIM calculations and a realistic model for the radial distribution of flickering are required. This is beyond the scope of this paper. However, a simple toy model can already provide an approximation, demonstrating, if not the detailed properties, but at least the existence of a hysteresis. Both, quiescent and outbursting parts of the disk are taken to radiate like black bodies. During outburst the effective temperature is a function of the mass of the primary star, the local mass transfer rate $\dot{M}$ (here assumed to be constant) and the distance from the centre of the disk (Frank et al. 2002, eq. 5.43 of). I assume the temperature during quiescence to decrease linearly for $T_i$ at the inner disk rim to $T_o$ at the outer rim. $T_i$ and $T_o$ are free parameters of the model. I simulate the outburst light curve by considering the disk to be composed of concentric rings which are either in quiescence or in outburst and summing up their monochromatic flux at the effective wavelength of 6650 Å of the broad Kepler bandpass (Brown et al. 2011) as a function of time. The velocity of the heating front its taken to be $c_s = c_h$ (Hameury 2020), where $c_h$ is the Shakura-Sunyaev viscosity parameter in the hot state, and $c_s$ is the local sound speed which can be calculated from Eqs., 5.35, 5.26, and 5.49 of Frank et al. (2002). The cooling front is assumed to propagate more slowly by a constant factor of the heating front speed. But note that the front speeds only determine the time scale of the outburst and have no bearing on the flickering hysteresis. Transforming fluxes into magnitudes, it is then possible to construct the dependence of the flickering amplitude on the magnitude during both, outburst rise and decline.

The model has several parameters, but most of these have only a small influence on the results. For the outer disk radius a typical value of $0.4a$ (Warner 1995) is taken, where $a$ is the component separation, determined by the stellar masses and the orbital period. For the white dwarf mass I assume the average primary star mass of 0.83 $M_\odot$ of CVs (Zorotovic et al. 2011), and the mass ratio $q = 0.16$ (Osaki & Kato 2013b) and
the period of V1504 Cyg. The white dwarf radius according to Nauenberg (1972) defines the inner disk radius. The eventual presence of (constant) third light (p.e., the secondary star, a hot spot at the disk rim, or the white dwarf) is neglected. The disk is assumed to be seen face on.

While this simple model is only capable to approximately replicate the outburst shape and falls somewhat short to simultaneously reproduce the outburst amplitude, the hysteresis amplitude (i.e., the difference between the upper and the lower branch as a function of magnitude) and the magnitude at the maximum of the hysteresis amplitude curve, Fig. 12 shows that, depending on the choice of parameters, the model can produce a sizable hysteresis of the magnitude – flickering amplitude relation. It turns out that this curve depends mostly on $M$, $T_i$ and $T_o$.

The left hand column of the figure shows this relation (i.e., $\Delta m$ vs. $A_{60}$) for an assumed isothermal (probably unrealistic) quiescent disk with different temperatures, all for a constant mass transfer rate of $2 \times 10^{-9} M_\odot/\text{yr}$. As in Fig. 6 the blue and red branches represent the rise to and decline from outburst, respectively. The fractional flickering flux in quiescence and outburst are free parameters of the model. They have been chosen such as to roughly reproduce $A_{60}$ as observed during the respective states in V1504 Cyg. The hysteresis is strongly expressed if the disk temperature in quiescence is relatively high (upper left frame), but then the outburst amplitude remains much lower than observed. A cooler quiescent disk (4000 K) yields the observed outburst amplitude, but then the amplitude of the hysteresis is less than half of what is observed in V1504 Cyg (lower left frame). In the central column of the figure a temperature gradient in the quiescent disk is assumed, again fixing $M$ to $2 \times 10^{-9} M_\odot/\text{yr}$. The hysteresis amplitude is then strongly dependent on $T_o$ and vanishes when $T_o$ becomes small. This is easily understood because then the ratio of the surface brightness of inner and outer quiescent disk is not much different from that of the disk in outburst. Finally the right hand column shows the $\Delta m - A_{60}$ relation for an isothermal disk, assuming different values for $M$. The outburst amplitude grows with increasing $M$, but the hysteresis amplitude decreases.

Thus, this simple scenario, while not being able to reproduce all features of the observed $\Delta m - A_{60}$ relation, is capable – adopting reasonable parameters – to explain the very existence of a hysteresis, quod erat demonstrandum. Details such as the observed convergence of the two branches at high magnitudes as well as the hysteresis amplitude are not well modelled. Moreover, by design the model cannot reproduce the flat part of the $\Delta m - A_{60}$ relation at high magnitudes, observed in all current objects except V1504 Cyg (disconsidering the unusual system KIC 9202990). On the other hand, selecting suitable parameters, the model has no problems to explain the apparent absence of a hysteresis in V447 Lyr and V516 Lyr.

Turning the attention now to the frequency spectrum of the flickering and particularly to details of the high frequency slope of the power spectra on the double logarithmic scale, in past investigations the focus has often been restricted to break points, i.e., frequencies at which the slope and thus the spectral index exhibits a more or less sudden change (e.g., Dobrotka et al. 2012, 2014, 2017; Scaringi et al., 2012; Scaringi 2014). Various models have been put forward to reproduce the observed features in a variety of different systems. They have been met with mixed success, indicating that none of them is sufficiently general to explain the variety of observational aspects of flickering. Moreover, it is not immediately obvious how to interpret breaks in the power spectra and what determines specific numerical values of the spectral index.

Concerning the objects of the present study, Dobrotka & Ness (2015) investigated the frequency spectrum of the same Kepler data of V1504 Cyg. A re-analysis of these data, together with an analysis of the Kepler data of V344 Lyr was published by Dobrotka et al. (2016). In both stars they find a break at $\log(f) = 1.5$ in quiescence$.^4$ During outburst, this break persists, and additional breaks appear at $\log(f) = 1.9$ and between 2.1 and 2. Dobrotka et al. (2017) conclude that the low flickering frequencies originate from regions affected by the outburst (the accretion disk or its inner edge) while the high frequencies are not affected and originate in an inner hot geometrically thick corona. The authors suggest that flickering in both, quiescence and outburst, is generated by turbulent mass accretion, but during outburst an additional non-turbulent radiation source must be present.

Comparing the present results with those of the previous studies, Fig. 10 indicates that the slope of the quiescent power spectra of V1504 Cyg and V344 Lyr indeed changes close to $\log(f) = 1.5$ to a degree that the range of lower frequencies was not used here to measure the spectral index. Additionally, the high frequency regime of V1504 Cyg is not perfectly linear but exhibits a slight hump in the approximate range $2.35 \leq \log(f) \leq 2.6$.

$^4$ Note that Dobrotka et al. (2016) express frequencies in units of Hz, while I use units of $d^{-1}$ in this study.
log(f) ≤ 2.65 which was also seen by Dobrotka & Ness (2015) (see their fig. 2; note the different definition of the y-axis in that figure). In contrast, I could not clearly identify the additional break points claimed by Dobrotka et al. (2016) to be present during outburst.

It is not the purpose of this study to construct yet another model in order to quantitatively reproduce the spectral index or the break points. I rather contend myself to investigate qualitatively whether the index changes during the outburst cycle or over time. Thus, the exact absolute value of the spectral index is less important that its variation. This permits to ignore the slight deviations from linearity of the high frequency power spectrum slope which data noise inhibits anyway to be detected in the individual 8-hour sections of the light curves. The average spectral index over the approximately linear part of the power spectra is therefore sufficient to characterize the frequency behaviour of the flickering.

The long-term decrease of γ, seen in V344 Lyr and the slight dependence of the average γ on the epoch in KIC 9202990 (Fig. 11), may come as a surprise because there is no apparent correlation with other changes in the long term behaviour of the systems. Therefore, I just document this feature here, without endeavouring to explain it.

On the other hand, the systematic variations of γ over the outburst cycle in V1504 Cyg and V344 Lyr indeed attest to changes of the flickering light source depending on the brightness and thus the state of the accretion disk. However, this dependence is not the same for the two systems. While the average spectral index is, on average, slightly smaller during the rise to outburst than during decline. In two other dwarf novae higher noise levels does not permit to verify if a similar hysteresis exists or not. Qualitatively, the hysteresis can be explained in a DIM scenario for dwarf nova outbursts with the flickering amplitude being lower/higher in parts of the accretion disk in a high/low state, and a smaller radial temperature gradient in the low state parts compared to the high state parts.

(3) The spectral index also varies around the outburst cycle, however, the dependence on magnitude is not the same for the investigated systems. A hysteresis similar to the one seen in the flickering strength is present in V1504 Cyg and possibly also in V344 Lyr, the index being lower during the rise to outburst than during decline at the same brightness level. This can be explained in the same scenario as above, assuming that the frequency distribution of the flickering is different in high and low state parts of the accretion disk.

(4) The flickering properties as a function of brightness of the unusual system KIC 9202990 which, instead of normal dwarf nova outburst exhibits a continuous series of small amplitude variations interpreted as stunted outbursts, are different from those of “well behaved” dwarf novae.

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DATA AVAILABILITY

All data used in the present study are publically available at the Barbara A. Mikulski Archive for Space Telescopes (MAST): https://mast.stsci.edu/portal/Mashubclients/MAST/Portal.html.

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7 SUMMARY

In this study, I took advantage of the unparallel quantity and quality of high cadence data observed by the Kepler satellite of several dwarf novae to investigate some aspects of flickering in these systems around their outburst cycles. In particular, the strength of the flickering and the spectral index of the high frequency part of the flickering power spectrum were measured as a function of magnitude. The main results can be summarized as follows:

(1) In three of four investigated dwarf nova the tendency, suspected earlier by B21 based on data of lesser quality, for the flickering strength (on a magnitude scale) to remain practically constant when the system is above a certain brightness threshold and to increase strongly at fainter magnitudes, is confirmed.

(2) Two systems (V1504 Cyg and V344 Lyr) exhibit a clear hysteresis of the flickering strength around the outburst cycle in the sense that flickering at a given brightness is weaker on the rise to outburst than during decline. In two other dwarf novae higher noise levels does not permit to verify if a similar hysteresis exists or not. Qualitatively, the hysteresis can be explained in a DIM scenario for dwarf nova outbursts with the flickering amplitude being lower/higher in parts of the accretion disk in a high/low state, and a smaller radial temperature gradient in the low state parts compared to the high state parts.
