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Flickering of accreting white dwarfs: the remarkable amplitude–flux relation and disc viscosity

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ABSTRACT

We analyse optical photometric data of short term variability (flickering) of accreting white dwarfs in cataclysmic variables (KR Aur, MV Lyr, V794 Aql, TT Ari, V425 Cas), recurrent novae (RS Oph and T CrB) and jet-ejecting symbiotic stars (CH Cyg and MWC 560). We find that the amplitude–flux relationship is visible over four orders of magnitude, in the range of fluxes from 10^{29} to 10^{33} erg s^{-1} Å^{-1}, as a 'statistically perfect correlation with correlation coefficient 0.96 and p-value $\sim 10^{-28}$. In the above range, the amplitude of variability for any of our 9 objects is proportional to the flux level with (almost) one and the same factor of proportionality for all nine accreting white dwarfs with $\Delta F = 0.36(\pm 0.05) F_{\rm av}$, $\sigma_{\rm rms} = 0.086(\pm 0.011) F_{\rm av}$, and $\sigma_{\rm rms}/\Delta F = 0.24 \pm 0.02$. Overall, our results indicate that the viscosity in the accretion discs is practically the same for all nine objects in our sample, in the mass accretion rate range $2 \times 10^{-11} - 2 \times 10^{-7}$ M$_\odot$ yr^{-1}.

Key words: accretion, accretion discs – binaries: symbiotic – novae, cataclysmic variables.

1 INTRODUCTION

Cataclysmic variables (CVs) are close binary stars consisting of a late-type main sequence star which is transferring material to the white dwarf. Symbiotic stars included here are wide binaries in which material is transferred from an evolved red giant star to a white dwarf.

Flickering is one of the most intriguing characteristics of the accreting compact objects. It appears as broad-band stochastic light variations on time-scales of a few minutes with amplitude from a few × 0.01 mag to more than one magnitude. Random fluctuations of the brightness are observed throughout diverse classes of objects that accrete material on to a compact object (white dwarf, neutron star or black hole) – binary stars, X-ray binaries, Active Galactic Nuclei. The source of the flickering variations is the accretion disc – either the disc itself or some parts of the disc, e.g. bright spot or boundary layer. The first reported detection of flickering activity is by Pogson (1857) based on visual observations of the dwarf nova U Gem. Photoelectric observations identified the flickering as a common characteristic of the accretion process (e.g. Mumford 1966; Henize 1949; Robinson 1973). A quantitative study of the flickering properties in CVs has been performed by Bruch (1992), who defined several physical parameters to describe the phenomenon.

The amplitude–flux relation has previously been discovered for a few objects on an object-by-object basis. Here, we present data for nine accreting white dwarfs showing flickering in the optical bands. Our aim is to investigate the behaviour of the flickering amplitude and root mean square (rms) flux relative to the average flux of the hot component, examining the position of different objects on two diagrams: ΔF versus $F_{\rm av}$ and $\sigma_{\rm rms}$ versus $F_{\rm av}$.

2 OBSERVATIONS AND DATA ANALYSIS

We started to observe flickering of accreting white dwarfs in 1990. Over ≈25 yr of observations, we acquired photometry of rapid variability with the 2.0-m RCC, 50/70 cm Schmidt and 60 cm telescopes of the National Astronomical Observatory Rozhen, the 60 cm telescope of the Belogradchick Astronomical Observatory (Bulgaria), 1.0 m Nickel telescope at UCO/Lick Observatory on Mt. Hamilton near San Jose, CA (USA), and the fully robotic 2.0 m Liverpool Telescope[1] (Steele et al. 2004).

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Table 1. In the Table are given the name of the object, its type, N_{obs} (the number of light curves), total duration of the observations in hours, the brightness interval during our observations, the adopted distance in parsecs, the interstellar extinction, the adopted spectral type and visual band magnitude (m_B) of the mass donor, and finally the ratios amplitude/flux and rms/flux [**Extra column on right for symbol for each object??**].

Object	type	P_{orb}	N_{obs}	D[h]	min – max	d [pc]	E_{B-V}	donor	$\Delta F/F_{av}$	σ_{rms}/F_{av}
T CrB	RecN	227 d	31	46.6	m_U 10.5-11.9	960	0.14	M4III, $m_B \approx$11.8	0.397±0.109	0.083±0.023
RS Oph	RecN	455 d	76	139.7	m_B 11.1-13.2	1600	0.73	M2III, $m_B \approx$13.9	0.349±0.103	0.086±0.036
MWC 560	symbio	1931 d	21	46.6	m_U 9.3-11.5	2500	0.15	M5.5III, $m_B \approx$13.6	0.326±0.130	0.077±0.032
CH Cyg	symbio	15.6 yr	16	26.1	m_U 7.3-10.8	244	0.20	M6III, $m_B \approx$11.5	0.424±0.160	0.093±0.041
KR Aur	CV	3.91 h	12	42.2	m_B 13.1-18.9	1000	0.05	M1V, $m_B \approx$21.5	1.248±1.000	0.306±0.247
V425 Cas	CV	3.59 h	14	17.3	m_B 14.7-15.7	700	0.30	M3V, $m_B \approx$18.5	0.326±0.161	0.089±0.047
MV Lyr	CV	3.19 h	20	35.9	m_B 12.8-14.6	505	0.00	M4V, $m_B \approx$17.9	0.345±0.086	0.079±0.022
V794 Aql	CV	3.68 h	6	9.6	m_B 15.1-16.5	690	0.20	M1V, $m_B \approx$20.0	0.331±0.079	0.088±0.019
TT Ari	CV	3.30 h	8	32.0	m_B 10.4-10.9	335	0.05	M3.5V, $m_B \approx$18.5	0.318±0.073	0.069±0.015

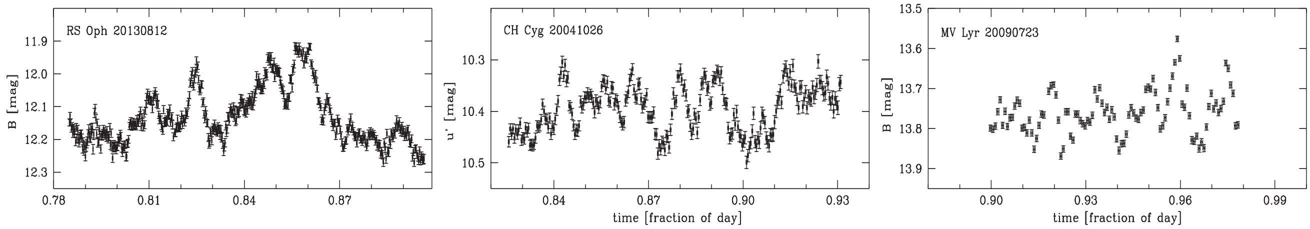

Figure 1. Example light curves of RS Oph, CH Cyg and MV Lyr. The date of observations is indicated in each panel.

We have obtained more that 396 h (204 light curves) in total of observations of the flickering of the recurrent novae RS Oph and T CrB; of the jet ejecting symbiotic stars MWC 560 and CH Cyg, and of the CVs KR Aur, MV Lyr, V425 Cas, V794 Aql and TT Ari. In each run, brightness fluctuations on a time-scale of ~10 min are clearly visible.

To analyse brightness fluctuations, we begin by a conversion of the magnitudes into fluxes, adopting the calibration for a zero magnitude star of Bessell (1979). The observed flux during a given night was corrected for the contribution of the mass donor (red giant in case of symbiotic stars and red dwarf in case of CVs) and interstellar extinction. For the correction of the mass donor contribution we adopt B-band magnitudes and spectral types given in Table 1, and (U−B) and (B−V) colours for the corresponding spectral type given by Schmidt–Kaler 1982.

For each run, we calculate the following dereddened quantities: F_{max} – the maximum flux of the hot component; F_{min} – the minimum flux of the hot component; $\Delta F = F_{max} - F_{min}$ – peak-to-peak amplitude of the flickering; F_{av} – the average flux of the hot component:

$$F_{av} = \frac{1}{N} \sum_{i=1}^{N} F_i; \tag{1}$$

and the absolute rms amplitude of variability (the square-root of the light-curve variance):

$$\sigma_{rms} = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (F_i - F_{av})^2}. \tag{2}$$

Subsequently, we subtract the contribution expected from measurement errors. The corrections of ΔF and σ_{rms} for these measurement errors are small, in the range 1–4 per cent.

Our runs have durations from 21 to 468 min (typical duration is about 100 min), the number of the points in one run is between 17 and 2400 (typically about 200 points) and the exposure time ranges from 1 to 300 s. A few examples of our observations are presented in Fig. 1.

3 RESULTS

In Fig. 2, we plot the amplitude of the flickering versus the average flux of the hot component, on a logarithmic scale. These are the fluxes as observed on the Earth, corrected for the interstellar extinction. Each object is plotted with a different symbol: RS Oph – black plusses, T CrB – red crosses, MWC 560 – green squares, CH Cyg – blue diamonds, V425 Cas – magenta squares, KR Aur – green crosses, MV Lyr – blue triangles, V794 Aql – black diamonds, TT Ari – yellow crosses. The symbols used are the same in Figs 2, 3 and 4.

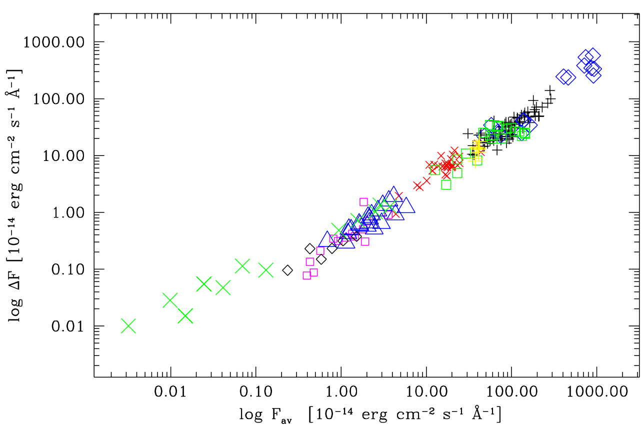

Figure 2. Amplitude of the flickering versus the average flux of the hot component, on a logarithmic scale for nine accreting white dwarfs (see Section 3 for details of the objects plotted). Estimated errors are less than or equal to the size of the symbols on the plot. Remarkably, above 2×10^{-15} erg cm^{-2} s^{-1} Å^{-1}, all data points lie on the same line with Y and X increasing/decreasing together.

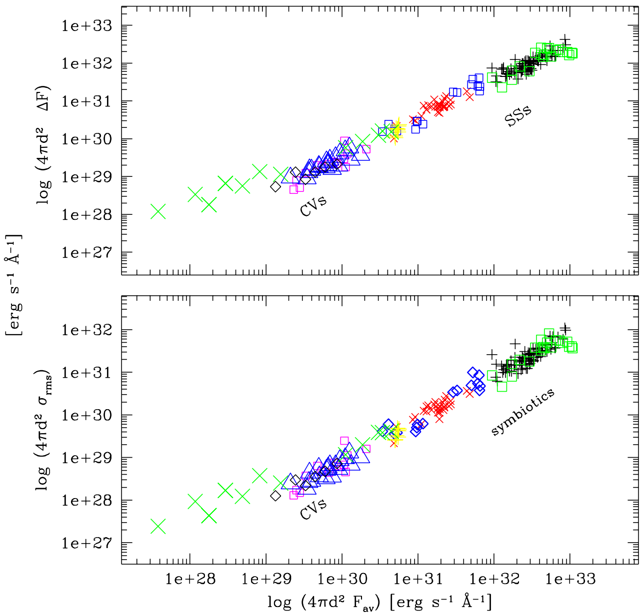

Figure 3. Amplitude (ΔF – top panel) and rms flux ($\sigma_{\rm rms}$) versus the average flux of the hot component on a logarithmic scale corrected for the distance and interstellar extinction. The symbols and the errors are the same as in Fig. 2. In the X-axis range from 10^{29} to 10^{33} erg s^{-1} Å^{-1} (almost) all data points lie on one straight line.

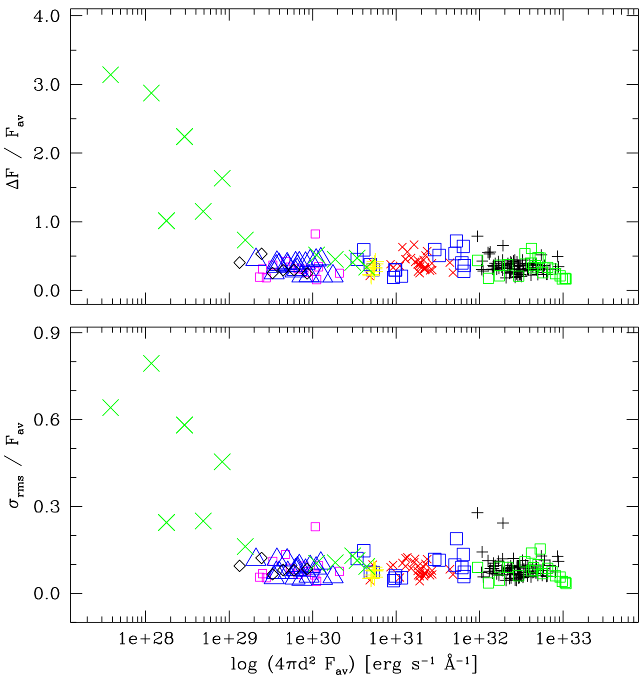

Figure 4. Normalized amplitude ($\Delta F/F_{\rm av}$ – top panel) and normalized rms ($\sigma_{\rm rms}/F_{\rm av}$) versus the average flux of the hot component. This figure is similar to Fig. 3, however the normalized quantities are plotted.

It is clearly apparent that for $F_{\rm av} \geq 2 \times 10^{-15}$ erg cm^{-2} s^{-1} Å^{-1} all 198 data points are located on a straight line with Y and X increasing/decreasing together.

The quantities corrected for the distance are plotted in Fig. 3. In this figure, we plot the amplitude of the flickering (ΔF, upper panel) and the rms ($\sigma_{\rm rms}$, lower panel) versus the average flux of the hot component. All the quantities are corrected for the distance using the distances given in Table 1. In Fig. 3, the objects located above $\approx 10^{31}$ erg s^{-1} Å^{-1} are symbiotic stars, and below this value are CVs. This reflects the fact that in symbiotics the mass donor is a red giant star and it is able to transfer more material than a red dwarf mass donor in a CV.

A comparison between Fig. 2 and the upper panel of Fig. 3 shows that the objects change their places and the relationship remains the same. For example CH Cyg, which is the closest object to the Earth in our sample, having a distance of only 244 pc, is located in the upper-right corner on Fig. 2. When the distance is taken into account (Fig. 3), the recurrent nova RS Oph is placed in the upper-right corner together with the jet-ejecting symbiotic MWC 560 – the objects having the highest mass accretion rates ($\sim 10^{-7}$ M$_\odot$yr^{-1}) among those in our sample.

In Fig. 3, it is seen that, when the quantity $4\pi d^2 F_{\rm av}$ is in the range of $10^{29} - 10^{33}$ erg s^{-1} Å^{-1}, all the objects lie on one straight line. Mathematical tests show that we have a 'statistically perfect correlation with Pearson correlation coefficient 0.99, Spearman's (rho) rank correlation 0.98, and significance $p - value \approx 10^{-40}$. We fit the data to a straight line in log–log space (Fig. 3), taking errors into account and obtain:

$$\log(4\pi d^2 \Delta F) = 0.996(\pm 0.043) \log(4\pi d^2 F_{av}) - 0.33(\pm 0.68) \quad (3)$$

$$\log(4\pi d^2 \sigma_{\rm rms}) = 0.994(\pm 0.042) \log(4\pi d^2 F_{\rm av}) - 1.10(\pm 0.44). \quad (4)$$

Thus, the relationship between the amplitude of variability and the average flux of the hot component is consistent with linearity for our 198 points in the range $10^{29} - 10^{33}$ erg s^{-1} Å^{-1}.

Our data are not evenly distributed among different objects, e.g. for RS Oph we have more than 70 light curves, while for V794 Aql only 6. To check the influence of this distribution, we applied bootstrap resampling (e.g. Davison & Hinkley 1997), selecting on a random basis five observations per object and repeating it $\sim$100 times. For each sample containing 45 points we recalculated the correlation and the result is always good, with correlation coefficient >0.95 and significance better than 10^{-28}. We repeated this procedure with six observations per object and the values are similar, thus confirming the result based on all data.

In Fig. 4, we plot the normalized quantities $\Delta F/F_{\rm av}$ and $\sigma_{\rm rms}/F_{\rm av}$. Most of the values are in the range $0.04 < \sigma_{\rm rms}/F_{\rm av} < 0.13$. There are a few points that are considerably above the average. The deviating points are: V425 Cas (20090723), RS Oph (20120815) and KR Aur (2009 January–February). The record in our sample is the CV KR Aur, which in a low state achieves values $m_{\rm V} \approx 18.7$ mag, flickering amplitude 1.2 mag, $\Delta F/F_{\rm av} \sim 1.5$ and $\sigma_{\rm rms}/F_{\rm av} \sim 0.4$. When KR Aur is brighter than $m_{\rm B} \sim 16.5$ mag its flickering is similar to that of the other objects and follows the same straight line.

Excluding KR Aur in low state, we calculate mean values $\Delta F/F_{\rm av} \approx 0.362 \pm 0.045$, $\sigma_{\rm rms}/F_{\rm av} \approx 0.086 \pm 0.011$, and $\Delta F/\sigma_{\rm rms} \approx 4.2 \pm 0.4$. Our results imply that the normalized amplitude ($\Delta F/F_{\rm av}$), the normalized rms variability ($\sigma_{\rm rms}/F_{\rm av}$), and the ratio $\sigma_{\rm rms}/\Delta F$ are approximately independent of the source brightness over the range $10^{29} < 4\pi d^2 F_{\rm av} < 10^{31}$ erg s^{-1} Å^{-1} (see Fig. 4).

4 DISCUSSION

It is known that most of the accretion-powered sources exhibit random fluctuations in their flux. A fundamental characteristic of fast stochastic variability is the correlation between variability amplitude and average flux. This relation is valid over a wide-range of time-scales. Uttley, McHardy & Vaughan (2005) studied non-linear

X-ray variability of X-ray binaries and active galaxies and found a linear relation between rms and flux calculated from light-curve segments. The detection of this relation is reported for the galactic black hole binary Cyg X-1 and in the accreting millisecond pulsar SAX J1808.4-3658 (Uttley & McHardy 2001), in the ultraluminous X-ray source NGC 5408 X-1 (Heil & Vaughan 2010), in the extreme narrow-line Seyfert 1 galaxy *IRAS* 13224-3809 (Gaskell 2004) and in the bright Seyfert 1 galaxy Markarian 766 (Vaughan et al. 2003). This feature of the broad-band X-ray variability of accreting black holes in X-ray binaries and Active Galactic Nuclei is called the rms-flux relation. The light curves, obtained with the *Kepler* satellite, show the same linear relation in the case of the CVs MV Lyr (Scaringi et al. 2012), V1504 Cyg, and KIC8751494 (Van de Sande, Scaringi & Knigge 2015). This relationship was also detected in the recurrent nova RS Oph (Zamanov et al. 2015). The detection of the rms-flux relation in such different objects is a demonstration of the universal nature of accretion-induced variability (Scaringi et al. 2012). Here, we report the detection of a linear relationship between the rms variability amplitude and the mean flux, which is valid not only for a single object but for nine objects in accreting white dwarf binary systems. This relationship represents proof that the sources become more variable as they get brighter. The average flux of the hot component should be proportional to the mass accretion rate: $4\pi d^2 F_{\rm av} \propto M_{\rm wd}\ R_{\rm wd}^{-1}\ \dot{M}_{\rm acc}$. When the mass accretion rate increases, the average flux also increases, and the amplitude of the flickering also increases. The observations reported here indicate that the amplitude–flux relationship is valid over four orders of mass accretion rate, from about $\sim 2 \times 10^{-11}$ M$_\odot$ yr^{-1} to $\sim 2 \times 10^{-7}$ M$_\odot$ yr^{-1}. The amplitude of variability at any given moment and for any of our nine objects is proportional to the flux level with a very similar factor of proportionality for all nine accreting white dwarfs $\Delta F = 0.35(\pm 0.10)F_{\rm av}$ and $\sigma_{\rm rms} = 0.08(\pm 0.03)F_{\rm av}$. In the range $10^{29} < F_{\rm av} \le 10^{31}$ erg s^{-1} Å^{-1}, we have only four deviating points from 198 runs. This indicates that deviations from the rms-flux relationship do exist, but they are relatively rare, occurring in $\sim$2 per cent of the cases.

From Figs 3 and 4 it seems that the above relationship is not valid, when $F_{\rm av}$ is below 10^{29} erg s^{-1} Å^{-1}. This flux corresponds approximately to a mass accretion rate $\approx 2 \times 10^{-11}$ M$_\odot$ yr^{-1}. It might be connected with a critical mass accretion rate below which the disc structure changes. Because this suspicion is based only on one object (KR Aur), more data for low states of CVs would be helpful to determine where are the exact limits of validity of the linear rms-flux relation.

The broad-band variability is often attributed to inward propagating fluctuations driven by stochasticity in the angular momentum transport mechanism (Lyubarskii 1997). Cowperthwaite & Reynolds (2014) presented a non-linear numerical model for a geometrically thin accretion disc with the addition of stochastic non-linear fluctuations in the viscous parameter, capable of reproducing the observed linear rms-flux relationship in the disc luminosity. King et al. (2004) have found that the normalized rms variability is roughly a constant for each value of the viscosity parameter α. Following this, our results seem to indicate that the viscosity in the accretion discs (α) is almost identical for all nine objects in our sample, in the mass accretion rate range $2 \times 10^{-11} - 2 \times 10^{-7}$ M$_\odot$ yr^{-1}.

5 CONCLUSIONS

On the basis of 204 light curves of flickering of nine accreting white dwarfs in CVs and symbiotic stars, we calculated the amplitude and rms of variability. We report a remarkably linear relation between the peak-to-peak amplitude (and rms variability) and the mean flux holding in the range $10^{29} - 10^{33}$ erg s^{-1} Å^{-1}. In this range all objects follow practically the same relation. The amplitude–flux (ΔF versus $F_{\rm av}$) and rms-flux ($\sigma_{\rm rms}$ versus $F_{\rm av}$) relationships contain information about the dynamics of the infalling matter and are likely to occur in many more accreting systems.

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