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 9 accreting white dwarfs with $\Delta F = 0.36(\pm 0.05) F_{\text{av}}$, $\sigma_{\text{rms}} = 0.086(\pm 0.011) F_{\text{av}}$, and $\sigma_{\text{rms}}/\Delta F = 0.24 \pm 0.02$. Over all, our results indicate that the viscosity in the accretion discs is practically the same for all 9 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 – (stars:) novae, cataclysmic variables – binaries: symbiotic

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 $\times 0.01$ mag to more than one magnitude. Random fluctuations of the brightness are observed throughout diverse classes of objects that accrete material onto 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 disk - either the disk itself or some parts of the disk, 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 cataclysmic variables 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 9 accreting white dwarfs showing flickering in the optical bands. Our aim is to investigate the behaviour of the flickering amplitude and rms flux relative to the average flux of the hot component, examining the position of different objects on two diagrams: $\Delta F$ versus $F_{\text{av}}$ and $\sigma_{\text{rms}}$ versus $F_{\text{av}}$. 

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2 Observations and Data Analysis

We started to observe flickering of accreting white dwarfs in 1990. Over ≈25 years of observations, we acquired photometry of rapid variability with the 2.0m 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-meter Nickel telescope at UCO/Lick Observatory on Mt. Hamilton near San Jose, CA (USA), and the fully robotic 2.0 m Liverpool Telescope1 (Steele et al. 2004).

We have obtained more than 396 hours (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 timescale of ≈10 minutes are clearly visible.

To analyze brightness fluctuations, we begin by a conversion of the magnitudes into fluxes, adopting the calibration for a zero magnitude star of Bessel (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: \( F_{\text{max}} \) – the maximum flux of the hot component; \( F_{\text{min}} \) – the minimum flux of the hot component; \( \Delta F = F_{\text{max}} - F_{\text{min}} \) – peak-to-peak amplitude of the flickering; \( F_{\text{av}} \) – the average flux of the hot component during our observations, the adopted distance in parsecs, the interstellar extinction, the adopted spectral type and visual band magnitude (\( m \)) of the mass donor, and finally the ratios amplitude/flux and rms/flux.

In the Table are given the name of the object, its type, \( N_{\text{obs}} \) (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 (\( m \)) of the mass donor, and finally the ratios amplitude/flux and rms/flux.

| Object | type | \( P_{\text{orb}} \) | \( N_{\text{obs}} \) | D[\( \text{h} \)] | min – max | \( d \) [pc] | \( E_{B-V} \) | donor | \( \Delta F/F_{\text{av}} \) | \( \sigma_{\text{rms}}/F_{\text{av}} \) |
|--------|------|-----------------|----------------|-------|---------|---------|------------|-------|----------------|------------------|
| T CrB  | RecN | 227 d           | 31             | 46.6  | \( m_\odot \) | 10.5-11.9 | 960        | 0.14  | M4III, \( m_g \approx 11.8 \) | 0.397±0.109, 0.083±0.023 |
| RS Oph | RecN | 455 d           | 76             | 139.7 | \( m_\odot \) | 11.1-13.2 | 1600       | 0.73  | M2III, \( m_g \approx 13.9 \) | 0.349±0.103, 0.086±0.036 |
| MWC 560| symbio| 1981 d          | 21             | 46.6  | \( m_\odot \) | 9.3-11.5  | 2500       | 0.15  | M5.5III, \( m_g \approx 13.6 \) | 0.326±0.130, 0.077±0.032 |
| CH Cyg| symbio| 15.6 yr         | 16             | 26.1  | \( m_\odot \) | 7.3-10.8  | 244        | 0.20  | M6III, \( m_g \approx 11.5 \) | 0.42±0.160, 0.095±0.041 |
| KR Aur| CV   | 3.91 h          | 12             | 42.2  | \( m_\odot \) | 13.1-18.9 | 1000       | 0.05  | M1V, \( m_g \approx 21.5 \) | 1.248±1.000, 0.306±0.247 |
| V425 Cas| CV | 3.59 h          | 14             | 17.3  | \( m_\odot \) | 14.7-15.7 | 700        | 0.30  | M3V, \( m_g \approx 18.5 \) | 0.326±0.161, 0.089±0.047 |
| MV Lyr | CV   | 3.19 h          | 20             | 35.9  | \( m_\odot \) | 12.8-14.6 | 505        | 0.00  | M4V, \( m_g \approx 17.9 \) | 0.345±0.086, 0.079±0.022 |
| V794 Aql | CV | 3.68 h          | 6              | 9.6   | \( m_\odot \) | 15.1-16.5 | 690        | 0.20  | M1V, \( m_g \approx 20.0 \) | 0.331±0.079, 0.088±0.019 |
| TT Ari | CV   | 3.30 h          | 8              | 32.0  | \( m_\odot \) | 10.4-10.9 | 335        | 0.05  | M3.5V, \( m_g \approx 18.5 \) | 0.318±0.073, 0.069±0.015 |

Table 1. In the Table are given the name of the object, its type, \( N_{\text{obs}} \) (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 (\( m \)) of the mass donor, and finally the ratios amplitude/flux and rms/flux.

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

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 \( 2 \times 10^{-15} \text{erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1} \), all data points lie on the same line with Y and X increasing/decreasing together.

1 The Liverpool Telescope is operated on the island of La Palma by Liverpool John Moores University in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias with financial support from the UK Science and Technology Facilities Council.
the average flux of the hot component:

\[ F_{av} = \frac{1}{N} \sum_{i=1}^{N} F_i; \]  

(1)

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

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

(2)

Subsequently, we subtract the contribution expected from measurement errors. The corrections of \( \Delta F \) and \( \sigma_{rms} \) for these measurement errors are small, in the range 1–4 per cent.

Our runs have durations from 21 to 468 minutes (typical duration is about 100 minutes), 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 seconds. 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 Fig.2, Fig.3 and Fig.4.

It is clearly apparent that for \( F_{av} \geq 2 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ A}^{-1} \) 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 (\( \Delta F \), upper panel) and the rms (\( \sigma_{rms} \), 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 \( \approx 10^{31} \text{ erg s}^{-1} \text{ A}^{-1} \) 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 (\( \approx 10^{-7} M_\odot \text{ yr}^{-1} \)) among those in our sample.

In Fig.3 it is seen that, when the quantity \( 4\pi d^2 F_{av} \) is in the range of \( 10^{29} - 10^{33} \text{ erg s}^{-1} \text{ A}^{-1} \), 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 \( p – \text{value} \approx 10^{-40} \). We fit the data to a straight line in log-log space (Fig. 3), taking errors into account and obtain:

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

(3)

\[ \log(4\pi d^2 \sigma_{rms}) = 0.994(\pm 0.042) \log(4\pi d^2 F_{av}) - 1.10(\pm 0.44) \]  

(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 \( 10^{29} - 10^{33} \text{ erg s}^{-1} \text{ A}^{-1} \).

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 5 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 6 observations per object and the values are similar, thus confirming the result based on all data.

In Fig.4 we plot the normalized quantities \( \Delta F/F_{av} \) and \( \sigma_{rms}/F_{av} \). Most of the values are in the range \( 0.04 < \sigma_{rms}/F_{av} < 0.13 \). There are a few points that are considerably above the average. The deviating points are: V425 Cas (20090723), RS Oph (20120815) and KR Aur (January - February 2009). The record in our sample is the cataclysmic variable KR Aur, which in a low state achieves values \( m_y \approx 18.7 \text{ mag} \), flickering amplitude 1.2 mag, \( \Delta F/F_{av} \sim 1.5 \) and \( \sigma_{rms}/F_{av} \sim 0.4 \). When KR Aur is brighter than \( m_y \sim 16.5 \text{ mag} \) 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 \( \Delta F/F_{av} \approx 0.362 \pm 0.045, \sigma_{rms}/F_{av} \approx 0.086 \pm 0.011 \), and \( \Delta F/\sigma_{rms} \approx 4.2 \pm 0.4 \). Our results imply that the normalized amplitude \( (\Delta F/F_{av}) \), the normalized rms variability \( (\sigma_{rms}/F_{av}) \), and the ratio \( \sigma_{rms}/\Delta F \) are approximately independent of the source brightness over the range \( 10^{29} < 4\pi d^2 F_{av} < 10^{31} \text{ erg s}^{-1} \text{ A}^{-1} \) (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 timescales. 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 ultra-luminous 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 cataclysmic variables MV Lyr (Searangi et al. 2012),
it seems that the above relations hold only for a single object but for 9 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: $F_{\text{av}} \propto \dot{M}_{\text{acc}}$. 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 9 objects is proportional to the flux level with a very similar factor of proportionality for all nine accreting white dwarfs $\Delta F = 0.35 (\pm 0.10) F_{\text{av}}$ and $\sigma_{\text{rms}} = 0.08 (\pm 0.03) F_{\text{av}}$. In the range $10^{29} < F_{\text{av}} < 10^{31} \ erg \ s^{-1} \ \AA^{-1}$, we have only 4 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 Fig.3 and Fig.4 it seems that the above relationship is not valid, when $F_{\text{av}}$ is below $10^{29} \ erg \ s^{-1} \ \AA^{-1}$. 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 broadband variability is often attributed to inward propagating fluctuations driven by stochasticity in the angular momentum transport mechanism (Lyubarski 1997). Cowperthwaite & Reynolds (2014) presented a non-linear numerical model for a geometrically thin accretion disk with the addition of stochastic non-linear fluctuations in the viscous parameter, capable of reproducing the observed linear rms-flux relationship in the disk luminosity. King et al. (2004) have found that the normalized rms variability is roughly a constant for each value of the viscosity parameter $\alpha$. Following this, our results seem to indicate that the viscosity in the accretion disks ($\alpha$) is almost identical for all 9 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 relationship between the peak-to-peak amplitude (and rms variability) and the mean flux holding in the range $10^{29} - 10^{33} \ erg \ s^{-1} \ \AA^{-1}$. In this range all objects follow practically the same relation. The amplitude - flux ($\Delta F$ versus $F_{\text{av}}$) and rms - flux ($\sigma_{\text{rms}}$ versus $F_{\text{av}}$) relationships contain information.
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about the dynamics of the infalling matter and are likely to occur in many more accreting systems.

REFERENCES

Bessell, M. S. 1979, PASP, 91, 589
Bruch, A. 1992, A&A, 266, 237
Cowperthwaite, P. S., & Reynolds, C. S. 2014, ApJ, 791, 126
Davison, A.C., & Hinkley, D. V., Bootstrap Methods and Their Application, Cambridge Univ. Press, 1997
Gaskell, C. M. 2004, ApJ, 612, L21
Heil, L. M., & Vaughan, S. 2010, MNRAS, 405, L66
Henize, K. G. 1949, AJ, 54, 89
King, A. R., Pringle, J. E., West, R. G., & Livio, M. 2004, MNRAS, 348, 111
Lyubarskii, Y. E. 1997, MNRAS, 292, 679
Mumford, G. S. 1966, ApJ, 146, 411
Pogson, N. 1857, MNRAS, 17, 200
Robinson, E. L. 1973, ApJ, 183, 193
Scaringi S., Kording E., Uttley P., Knigge C., Groot P. J., Still M., 2012, MNRAS, 421, 2854
Schmidt-Kaler Th., 1982, in Landolt-Börnstein, Vol. I/2b, p. 15, Springer Berlin Heidelberg
Steele, I. A., Smith, R. J., Rees, P. C., et al. 2004, Proc. SPIE, 5489, 679
Uttley, P., & McHardy, I. M. 2001, MNRAS, 323, L26
Uttley, P., McHardy, I. M., & Vaughan, S. 2005, MNRAS, 359, 345
Van de Sande, M., Scaringi, S., & Knigge, C. 2015, MNRAS, 448, 2430
Vaughan, S., Edelson, R., Warwick, R. S., & Uttley, P. 2003, MNRAS, 345, 1271
Zamanov, R. K., Latev, G., Boeva, S., Sokoloski, I.L., K. Stoyanov, et al. 2015, MNRAS, 450, 3958

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