The universal nature of accretion-induced variability: the rms–flux relation in an accreting white dwarf

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ABSTRACT

We report the discovery of a linear relationship between the root mean square (rms) variability amplitude and the mean flux in the accreting white dwarf binary system MV Lyrae. Our light curve, obtained with the *Kepler* satellite, spans 633 d with quasi-continuous 58.8-s cadence resolution. We show, for the first time, that how this cataclysmic variable displays linear rms–flux relations similar to those observed in many other black hole binaries, neutron star binaries and active galactic nuclei. The phenomenological similarity between the rms–flux relation observed here and in other X-ray binaries suggests a common physical origin for the broad-band variability, independent of source type, mass or size of the compact accretor. Furthermore, we infer the viscosity parameter, α, and disc scale height, H/R, using two independent methods. In both cases, both values are found to be uncomfortably high to be accommodated by the disc instability model.

Key words: accretion, accretion discs – black hole physics – binaries: close – stars: individual: MV Lyrae – novae, cataclysmic variables – stars: oscillations.

1 INTRODUCTION

Compact interacting binaries are close binary systems usually consisting of a late-type star transferring material on to a compact object such as a black hole (BH), neutron star (NS) or a white dwarf (WD) via Roche lobe overflow. With an orbital period of the order of hours, the transferred material from the donor star forms an accretion disc surrounding the compact object in order to conserve angular momentum. The dynamics and physics governing the flow of matter accreting on to compact objects is however still debated. BH and NS compact binary systems are powerful and highly variable sources in X-rays, and it is by studying the fluctuations in X-ray luminosities that we have made progress towards understanding the physics involved within accretion discs (Belloni 2007; van der Klis 2007). For example, thanks to the *Rossi X-Ray Timing Explorer* (*RXTE*), van der Klis et al. (1996) have been able to detect fast (kHz) quasi-periodic oscillations (QPOs) in NS binaries, associating these with the inner edges of the accretion disc. The detected kHz QPOs can immediately be used to constrain the mass and radius of the NS (Miller, Lamb & Psaltis 1998).

Variability is a common characteristic of X-ray binary systems (XRBs, consisting of NS or BH accretor), cataclysmic variables (CVs, consisting of a WD accretor) and active galactic nuclei (AGN, where the accretor is a supermassive BH). Specifically, the power spectrum of this variability consists of two components: single or multiple QPOs and an aperiodic broad-band noise component spanning several decades in temporal frequency. QPOs have been extensively studied in a number of accreting sources, ranging from WD binaries (Warner 2004; Pretorius, Warner & Woudt 2006), to supermassive BHs at the centre of AGN (Gierliński et al. 2008). On the other hand, the properties of the broad-band noise component have been examined in detail only in XRBs and AGN.

One feature of the broad-band noise X-ray variability which seems to be ubiquitous in XRBs and AGN is the so-called root mean square (rms)–flux relation, which is a linear relationship between the absolute rms amplitude of variability and the flux, such that the sources become more variable as they get brighter (Uttley & McHardy 2001; Gleissner et al. 2004; Uttley, McHardy & Vaughan 2005; Heil & Vaughan 2010). The rms–flux relation is remarkably linear and applies over a broad range of time-scales, so that the rms of high-frequency variations correlates with those at low frequencies (Uttley et al. 2005). Crucially, the rms–flux relation is observed while the power-spectrum shape is itself stationary, implying that the rms–flux relation is a fundamental property of the

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variability process, and not connected with other processes which can change the variability properties on longer time-scales. Finally, it can be shown that the rms–flux relation predicts a log-normal distribution of fluxes and implies that the variability process is non-linear (Uttley et al. 2005). The current most favoured model to explain the rms–flux relation, as well as many other features of the variability in XRBs and AGN, is the propagating fluctuation model (Lyubarskii 1997; Kotov, Churazov & Gilfanov 2001; Arévalo & Uttley 2006). In this model, the observed variability is associated with modulations in the effective viscosity of the accretion flow at different radii. More specifically, the model assumes that, at each radius, the viscosity – and hence accretion rate – fluctuates on a local viscous time-scale around the mean accretion rate, whose value is set by what is passed inwards (again on the viscous time-scale) from larger radii. The overall variability of the accretion rate in the innermost disc regions is therefore effectively the product of all the fluctuations produced at all radii.

For CVs, the presence of broad-band noise in the power spectrum has been recognized for many years and is usually referred to as 'flickering' in the literature. However, the methods employed to study XRB light curves have not been applied to CV data. The properties of flickering have been mainly studied through the use of eclipse maps (e.g. Baptista & Bortoletto 2004), which have identified the existence of two different and independent sources of flickering: the low- and high-frequency flickering components. The low-frequency component originates from the overflowing gas stream from the secondary star, and is associated with the mass-transfer process. The high-frequency component, on the other hand, originates from the inner accretion disc region, and no evidence of variable emission from the hotspot, gas stream or WD has been observed (contrary to some previous suggestions; see Bruch 1992, 2000).

XRBs and AGN, which do show the rms–flux relation, share many properties with CVs. Both XRBs and CVs are observed to exhibit large-amplitude outbursts, which are theoretically explained as arising due to thermal/viscous instabilities in the accretion discs surrounding the compact objects (Shakura & Sunyaev 1973). Furthermore, similar to XRBs, CVs also display outflowing jets in conjunction with specific changes in the spectral energy distribution (Körding et al. 2008). Therefore, it is natural to suspect that CVs should also show behaviour associated with a fluctuating accretion flow, including the rms–flux relation which is seen in accreting BH and NS. However, although CVs share many similarities with XRBs and AGN, they also differ substantially in other respects. Specifically, the radius of a WD is over an order of magnitude larger than that of an NS or the event horizon of a BH. Because of this, accreting WDs are not subject to the effects of strong gravity. Additionally, accreting WDs have not been observed to display a Comptonized component as in XRBs and AGN, and furthermore they do not possess the extreme magnetic fields which are found in some NS. Therefore, it remains an important open question as to whether accreting WDs should show the same rms–flux behaviour as seen in XRBs and AGN.

The broad-band noise component, present in XRBs and AGN, is well studied because of the high-throughput X-ray missions with good timing capability (*RXTE*, *XMM–Newton*), allowing very short cadence (down to $\approx$ms) observations, at high sensitivities. In the optical, Gandhi (2009) observed three XRBs with ULTRACAM (Dhillon et al. 2007) and, as expected, also found that the light curves display similar rms–flux relations as those observed in the X-rays (although the optical emission could possibly originate from the jet and not the disc). Accreting WDs are faint in X-rays, since

their gravitational potential wells are not as deep as those of XRBs (so they show lower inner disc temperatures) and also (unlike AGN and XRBs) they do not seem to possess strong Comptonizing coronae. Because of this, detailed timing studies in the X-ray region have not been possible for disc-fed WDs, and most timing studies of these systems concentrated on optical light. Specifically, a series of papers (Warner 2004; Pretorius et al. 2006) already noted analogies between the QPOs observed in CVs and those observed in XRBs. However, detailed analysis of the broad-band noise component in CVs was so far not as straightforward as for XRBs. The reason for this is twofold: first, the broad-band noise component displays, in the optical, low-amplitude, few per cent fractional rms variations requiring sensitive cameras; secondly, the broad-band noise component can only be studied with long, continuous, observations. This is because optical broad-band noise is thought to be generated further out in the accretion disc compared to X-rays, and is thus observed on longer time-scales. Furthermore, broad-band noise is a stochastic process, requiring statistical studies of many realizations. This, in turn, demands long continuous observing. In order to truly assess whether accreting WDs display the rms–flux relation, and thus determine if this phenomenon is indeed ubiquitous in all accreting compact objects, irrespective of accretor type, a sensitive, long, high-cadence and continuous light curve in the optical light is required. This kind of observation has only now become possible, thanks to the *Kepler* satellite (Koch et al. 2010).

Here we analyse the *Kepler* light curve of the accreting WD system MV Lyrae (one of about 14 CVs known to exist within the *Kepler* field of view), and show that it does indeed exhibit an rms–flux relation similar to that observed in Cyg X-1 by Gleissner et al. (2004). MV Lyrae is a VY Scl nova-like system, spending most of its time in the high state ($V \approx 12$–13) and occasionally (every few years) undergoing short-duration (weeks/months) drops in brightness ($V \approx 16$–18; Hoard et al. 2004). It is not clear why MV Lyrae, and all VY Scl type stars, undergo this kind of behaviour, but it is known that these systems have extremely low mass-transfer rates at their minimum brightness (6×10^{-10} M$_\odot$; Hoard et al. 2004; Linnell et al. 2005). The inferred distance to MV Lyrae is $\approx$530 pc, with a secondary star cooler than 3500 K (Hoard et al. 2004). The orbital period of this CV is 3.19 h, with a binary mass ratio of 0.43 (Skillman, Patterson & Thorstensen 1995). We observed MV Lyrae during its final ascent, in a low-to-high luminosity transition, where its optical light mostly originates from its nearly face-on accretion disc (Skillman et al. 1995). In the next section we will describe the data acquisition and analysis, whilst our results and discussion are presented in Section 3.

2 DATA ANALYSIS

The MV Lyrae light curve was obtained with the *Kepler* satellite and provided to us by the Science Operations Centre[1] in reduced and calibrated form after being run through the standard data reduction pipeline (Jenkins et al. 2010). The response function for the photometry covers the wavelength range 4000–9000 Å. Here, we only consider the single aperture photometry (SAP) light curve and do not attempt to analyse the Pre-search Data Conditioning (PDC) light curve, as the latter is optimized for planet transit searches. As a consequence of this choice, data artefacts, which would have been removed by the PDC, remain in our *Kepler* SAP light curve. These

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[1] The data are proprietary. The first five quarters of *Kepler* observations will become public on 2012 January 7.
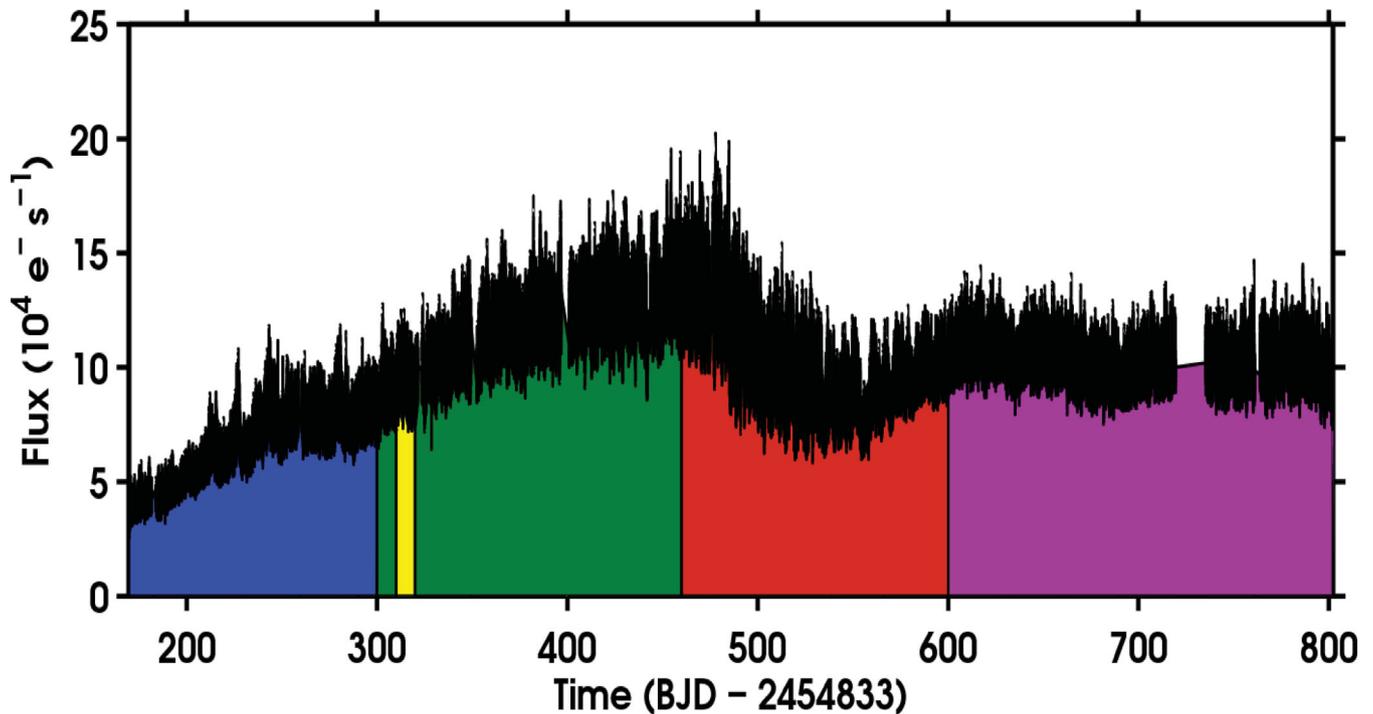
Figure 1. MV Lyrae light curve obtained by the *Kepler* satellite. The source was observed in short-cadence mode (58.8-s cadence) for 633 consecutive days. The light-curve segment within the yellow shaded region was used to produce the rms versus flux plot in Fig. 2. The blue, red, green and magenta regions have been used to produce the PSDs and rms–flux relations in Figs 3, 4 and 5. The last 233 days, marked by the magenta region, have been used to produce the flux distribution in Fig. 6.

artefacts are the result of rapid attitude tweaks to correct pointing drift, caused by the loss of fine pointing accuracy. This pointing accuracy loss is due to the spacecraft thrusters firing regularly every 3 days to desaturate the reaction wheels and can affect *Kepler* data for several minutes. Furthermore, data gaps occasionally occur due to *Kepler* entering anomalous safe modes. During such events no data are recorded and following data are often correlated with electronic warming. Further details of artefacts within *Kepler* light curves can be found in the *Kepler* Data Release Notes 3.[2] Here, we make no attempt to correct these artefacts, but simply remove them from the light curve.

Fig. 1 shows the short-cadence (58.8 s; Gilliland et al. 2010), barycentre-corrected light curve for MV Lyrae obtained during the first four quarters of *Kepler* operations. The light curve spans an interval of 633 d. The visible data gaps present in the light curve are due to the artefacts described above as well as the monthly data down-links. At first glance the light curve reveals an obvious steady increase in flux (over 1 mag) and also an increase in the flux variability (rms) during the rise.

To characterize the relationship between the rms variability and the mean flux, we followed a similar procedure as used by Gleissner et al. (2004) on Cyg X-1. Whilst Gleissner et al. (2004) used the mean power spectral density (PSD) level to measure rms, we directly measure it from the spread in the light-curve data points. First, the MV Lyrae light curve was split into 10-day segments. For each segment we computed 10-min flux averages and corresponding rms. All 10-day segments analysed displayed linear rms–flux relations after binning the 10-min averages by flux. One example is shown in Fig. 2. We carried out the same exercise employing smaller and
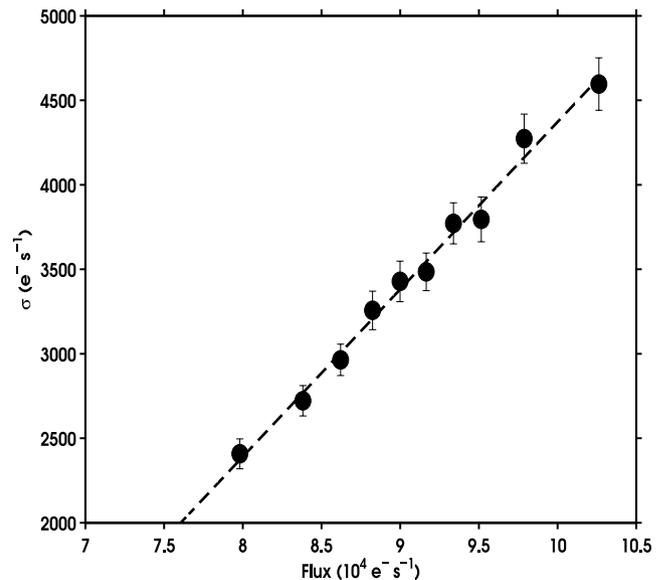
Figure 2. The rms–flux relation obtained from a 10-day segment (indicated by the yellow shade in Fig. 1) in MV Lyrae.

larger data segments, and longer and shorter averaging time-scales. In each case, we still recovered linear rms–flux relations. This is already strong evidence that the optical variability observed in the accreting WD is analogous to the X-ray variability seen in XRBs and AGN.

In order to quantify the linear relationship in Fig. 2, we modelled it with a function of the form (Uttley & McHardy 2001)

$$\sigma = k(F - C), \qquad (1)$$

where σ is the rms value, F is the flux in $e^-\,s^{-1}$, whilst k and C are the fit parameters. This linear model fits the general shape of the majority of our flux-sorted segments reasonably well, although occasionally large χ^2 values are recovered, implying that there exists some intrinsic scatter. This scatter can be caused by any non-stationarity in the variability processes which causes variations in the rms–flux relation on the 10-day time-scale of the segments. Furthermore, the presence of any frequency-varying QPO could break the linear rms–flux relation by varying the power spectrum over the frequency range used to measure the rms. In Fig. 3 we show the noise-subtracted PSD of the four coloured, independent, sections shown in the light curve of Fig. 1. The time-scales used to measure the rms are those at frequencies higher than 10 min, marked by the dashed black line in Fig. 3. For each segment, these rms values will respond to flux variations on longer time-scales, down to the 10-day length of the segment.

The PSDs shown in Fig. 3 show possible candidate QPOs at low frequencies and breaks just above 10^{-3} Hz. From the modelling performed by Arévalo & Uttley (2006), these breaks can be associated with the viscous time-scale at the innermost edges of the accretion disc. Above the break frequency, no annuli contribute significant variability power, and the PSD bends downwards. Given that the four different quadrants appear to display shifts in the break frequency, it is possible that mass accretion rate variations are displacing the inner edges of the accretion disc. Furthermore, at frequencies below the break, there appears to be candidate QPOs. These features at low frequencies, and the PSD break shifts, will be analysed and discussed in a paper in preparation: here we are only concerned with the high-frequency component observed in MV Lyrae.

Another interesting feature observed in MV Lyrae concerns the evolution of the rms–flux relation with both flux and time. In Fig. 4 we show the best-fitting lines for the rms–flux relations in all of our 10-day segments. In order to give a feel for the temporal evolution of the rms–flux relation, each colour represents a different section in the light curve, with the colours in Fig. 1 associated with those in
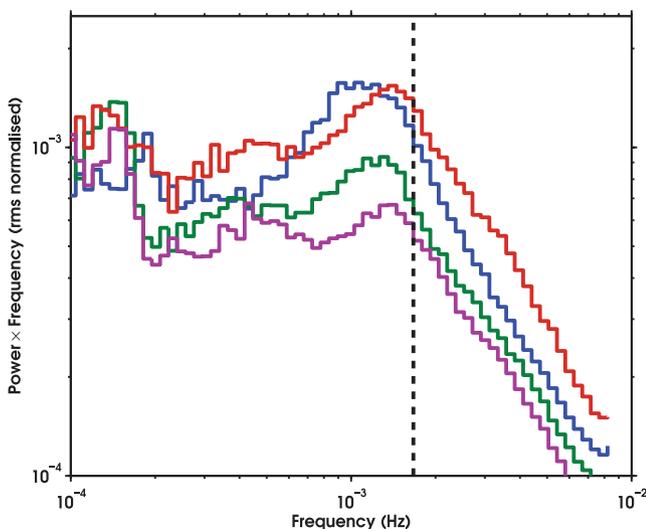
Figure 3. Power spectral distribution obtained from the MV Lyrae light curve shown in Fig. 1. The colour coding is analogous to that in Fig. 1, so that each independent PSD was obtained by the corresponding light-curve segment. The Poisson noise level, ranging between 2 and 3×10^{-5}, has been subtracted. In this paper we analyse frequencies higher than those marked by the black dashed line.

Fig. 4. Specifically, there appears to be a hysteresis-like behaviour in the evolution of the rms–flux relation within the broad-band noise of MV Lyrae. After about 150 days, the rms–flux relations seem to change behaviour and detach from the original trend (marked by blue lines in Fig. 4) and move to higher fluxes maintaining similar rms variability. In proximity of the peak flux in Fig. 1, after about 250 days of observations, the rms–flux relations seem to change behaviour once again during their flux descent (red lines), seemingly looping back to their original track after having reached a maximum rms variability of about 6 per cent. This behaviour has not been observed in any other accreting compact binary or AGN, and it is not clear at the time of writing what the physics behind this phenomenon is. In Fig. 5 we show the gradient and intercept for the best-fitting lines in Fig. 4, colour coded in the same way. Similar to the results obtained on the BH binary Cyg X-1 by Gleissner et al. (2004), the gradient and intercept in MV Lyrae seem to be correlated as well. This suggests that some fundamental and analogous process is giving rise to the rms–flux behaviour in both XRBs and CVs. Interesting is also the fact that in the gradient versus intercept plane there seem to be two distinct 'tracks': the rms–flux relations obtained from the blue and red light-curve segments seem to have a systematic offset in the gradient when compared to the green and magenta segments. Although we cannot properly quantify this behaviour at the moment with the available data, the evolution in Fig. 4 also seems to suggest that the rms–flux behaviour systematically changes during the light-curve evolution.

Finally, we also examined the flux distribution within the MV Lyrae light curve. Specifically, the observed fluxes in XRBs and AGN which do show the rms–flux relation are log-normally distributed. In order to perform this test, we produced a histogram of fluxes from the last 233 days (marked by the magenta region in Fig. 1) of the MV Lyrae light curve. We then fitted the histogram with both a symmetric Gaussian and a three-parameter log-normal model. The number of flux measurements per bin (N) was required to be at least 50 for the fits, with bin error assigned as $\sqrt{N}$. We performed this exercise on the last 233 days of the light curve, as these appear to be the most stationary in mean flux: a requirement for the log-normal behaviour to be expected (see Uttley et al. 2005; Gandhi 2009). Statistically, the Gaussian fit resulted in the goodness-of-fit parameter χ^2/d.o.f. of 18 802/269, whilst the log-normal fit resulted in 334/269. MV Lyrae clearly exhibits a log-normal flux distribution. The excess residual of our fit can be explained by the weak non-stationarity of the light curve, as also explained in Uttley et al. (2005) and Gandhi (2009).

3 DISCUSSION

We showed how the accreting WD MV Lyrae obeys a linear rms–flux relation like many other BH/NS compact interacting binaries and AGN. This is the first time that such a correlation was found in an accreting object other than a BH/NS X-ray binary or AGN. Furthermore, we showed how the rms–flux relation evolves with time, displaying what appears to be a hysteresis-like behaviour. The physics of this phenomenon is not yet understood, and it is the first time that it has been observed in an accreting compact object. Additionally, we confirmed our findings by ascertaining that the flux distribution of MV Lyrae follows a log-normal distribution, as seen in other accreting compact objects displaying the linear rms–flux relation.

The leading interpretation of the rms–flux relation is that of a fluctuating accretion disc (Lyubarskii 1997), where variations in the accretion rate occur at all radii and then propagate inwards on
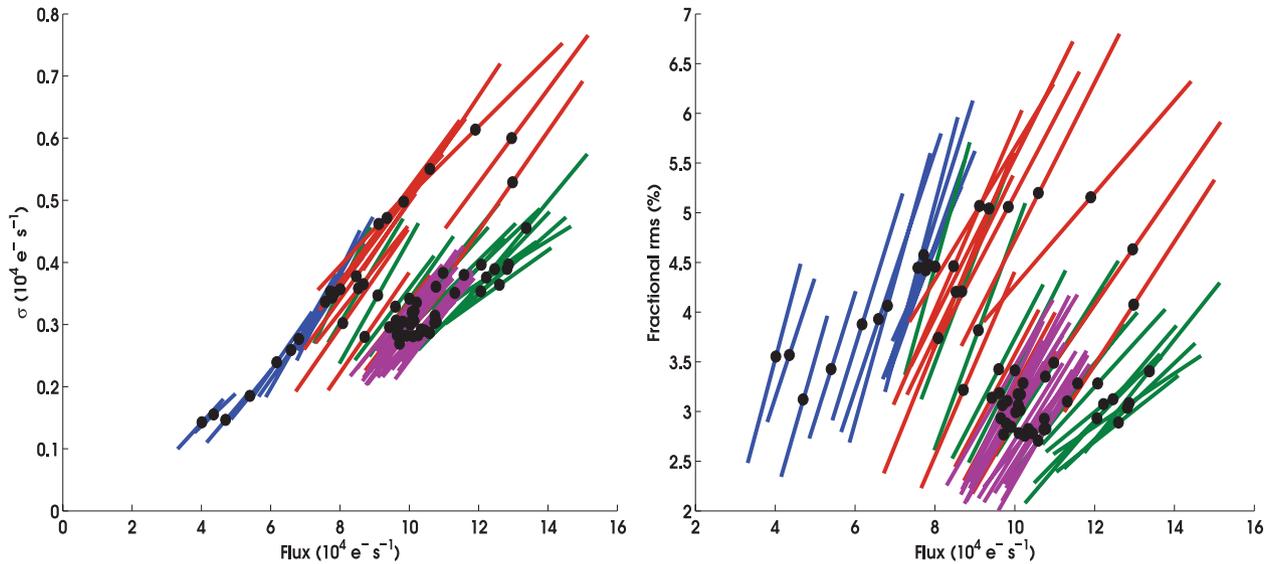
Figure 4. Right: the best-fitting lines for the rms–flux relations in all of our 10-day segments, one being shown in Fig. 2. In order to follow the temporal evolution of the rms–flux relations, colours are matched to those in Fig. 1. The black data points are the mean flux and mean rms values of the computed rms–flux relation fits. Left: same as above, but here the *y*-axis displays percentage fractional rms.
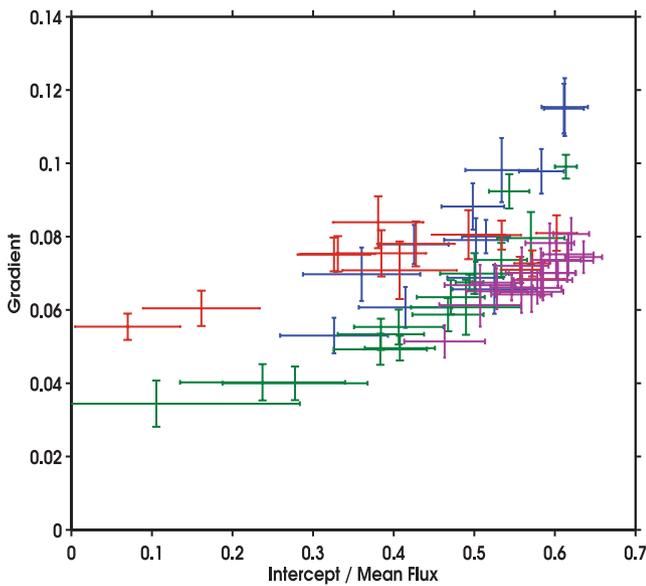
Figure 5. Best-fitting parameters (gradient and intercept from equation 1 normalized by the mean flux of each 10-day segment) from the rms–flux relations shown in Fig. 4. The colour coding is matched to those in Fig. 1.
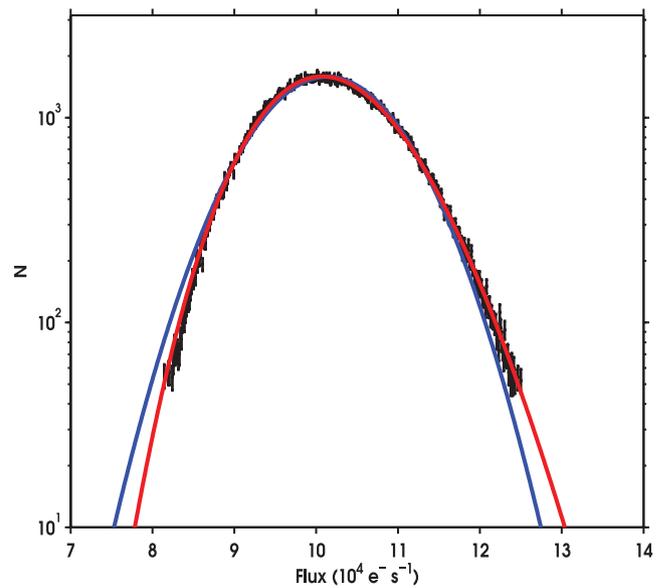
Figure 6. Binned frequency distribution of the mean source flux for the magenta section of the MV Lyrae light curve in Fig. 1 (black data points). A log-normal distribution fit is shown in red and a Gaussian fit in blue. A log-normal fit statistically describes the data better than a Gaussian.

the viscous time-scale within the accretion disc. These fluctuations couple together in a multiplicative way as they propagate down to the centre, so that low-frequency fluctuations produced at large radii modulate the higher frequency fluctuations produced further in. The multiplicative nature of the process will yield flux variations which follow a log-normal distribution, like the one in Fig. 6.

Churazov, Gilfanov & Revnivtsev (2001) have pointed out that, in a standard thin disc, viscous damping will smooth accretion rate fluctuations on the viscous time-scale. This means that, for the Lyubarskii (1997) model to work, the fluctuations must happen in a geometrically thick accretion disc flow (such as an advection-dominated flow or thick disc). We can use the PSD break just above 10^{-3} Hz (≈ 13 min, shown in Fig. 3), or the relative rms variations,

to constrain the viscosity parameter, α, and the disc scale height, H/R.

The PSD break in Fig. 3 can be associated with the viscous time-scale at the inner edges of the accretion disc (Arévalo & Uttley 2006). If this were the case, we would require a geometrically thick disc of about $H/R \approx 0.1$ (where H/R is the ratio of the vertical scale height to radius in the disc), and a viscosity parameter $\alpha \approx 1$. This is shown in Fig. 7, where we computed the viscous time-scales resulting from the standard α-disc solution of Frank, King & Raine (2002) (equation 5.68) as a function of H/R for an accretion disc extending all the way down to the WD surface at 7×10^8 cm. Both these values are considered to be high for a standard disc solution,
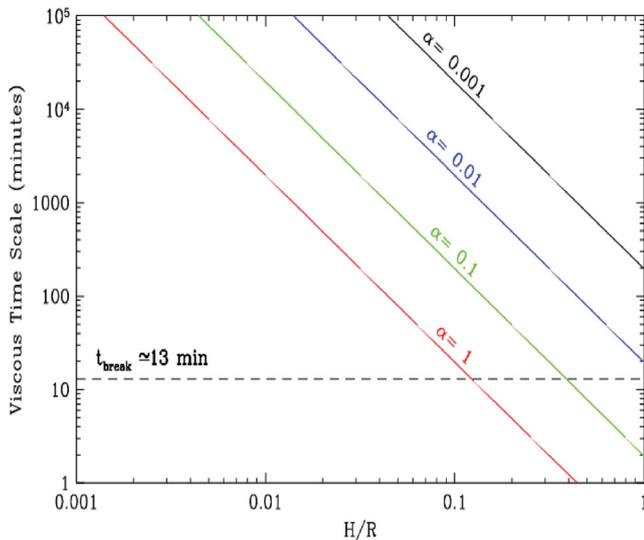
Figure 7. Viscous time scale as a function of *H/R* from the standard α-disc solution (Frank et al. 2002, equation 5.68). Each colour corresponds to a different α with black, blue, green and red corresponding to 0.001, 0.01, 0.1 and 1, respectively. The horizontal line marks the PSD break at ≈ 13 min.

and are pushing into uncomfortable limits of the Shakura & Sunyaev (1973) parameter space.

Following the procedure adopted by Baptista & Bortoletto (2004) on V2051 Oph, we also used the rms variability amplitude to obtain α and *H/R*. From the inferred 3 per cent rms variability (see Fig. 4) we obtain, similar to V2051 Oph, $\alpha \approx 0.16$. This estimate assumes an *H/R* value of about 10^{-2}, and is based on the effects of magnetohydrodynamic turbulence in an accretion disc, as modelled by Geertsema & Achterberg (1992). However, when the variability reaches 6 per cent in MV Lyrae, $\alpha \approx 0.62$, again pushing into uncomfortable limits of the Shakura & Sunyaev (1973) parameter space. To make α consistent with the expected viscosity of hot discs (Lasota 2001), the disc scale height, *H/R*, would have to increase to 0.1. This would then be in line with a geometrically thick, hot, disc. If this were the case, the rms variability amplitude would be an indicator of the disc scale height (assuming α to remain constant at its hot value of ≈ 0.1–0.2). More importantly, all the above estimates for the disc scale height and α are suggesting that the propagating fluctuation models may have difficulty in explaining the variability if the disc behaves like a 'standard' thin disc. One way to overcome these inconsistencies would be to invoke an overflowing gas stream, as mentioned by Baptista & Bortoletto (2004). This flow could exist above the standard thin accretion disc, extending all the way close to the WD surface, and possibly provide the thick disc required to explain the fast viscous time-scale inferred from the PSD breaks.

One other important implication of our discovery regards the interpretation of flickering noise in CVs in general. It has been recognized for many decades that almost all CVs display at least some optical flickering. Many suggestions have emerged in order to explain the origin of this flickering, by associating it with the accretion hotspot or the boundary layer close to the WD surface (Bruch 1992, 2000). More recently, Baptista & Bortoletto (2004) showed that CV flickering is caused by the existence of two different and independent sources. The low-frequency flickering component is caused by the overflowing gas stream from the secondary star, whilst the high-frequency component by the innermost regions of the accretion disc. Our result is in agreement with the interpretation that the high-frequency flickering is created within the accretion

disc. The fact that we observe the linear rms–flux relation within MV Lyrae (a canonical flickering CV) gives us confidence that the fluctuating accretion disc model is also at play within other CV systems. Furthermore, the observed fractional rms amplitude of ≈ 3 per cent, generally observed in MV Lyrae (see Fig. 4), is also similar to that found in V2051 Oph by Baptista & Bortoletto (2004).

Although it is clear from the Lyubarskii (1997) model that the variability is the result of modulations from an ensemble of coupled perturbations, the physical mechanism of variable emission is not yet known. Some suggested that synchrotron emission at the base of the outflowing jet could be a possibility (King et al. 2004). However, MV Lyrae is not known to display a jet (or synchrotron emission), and it is not likely that a Comptonized component is driving the rms–flux relation out to the large radii observed in the optical. More likely instead is that instabilities within the accretion disc are responsible for driving the continuum variability.

This interpretation is also supported by the recent results of Uttley et al. (2011). They showed that for XRBs the blackbody component in X-rays, associated with the disc, substantially leads the power-law component associated with the Comptonized region close to the compact object. Thus, the Comptonized region, thought to drive jet launching, is responding to changes in the accretion disc, and not vice versa. In this respect, we would expect MV Lyrae to display energy-dependent time lags in optical light (Arévalo & Uttley 2006), where the broad-band variability arising from bluer bands is lagging the variability observed from the redder ones: simply a consequence of the fact that the fluctuations are propagating inwards within the disc, affecting the redder outer edges before the bluer inner ones.

The rms–flux relation remains an enigmatic observational feature of all accreting compact objects, but it clearly contains information about the dynamics of the infalling material. Although the microphysics of accretion disc dynamics are not yet fully understood, our result strongly suggests that the processes involved are the same in all accreting compact objects, independent of mass, type and size. Our result has thus revealed yet another connection between accreting compact objects, suggesting that the physics of disc accretion are universal.

ACKNOWLEDGMENTS

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