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Flickering in CVs and Accretion Disc Viscosity

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Abstract

I review observational constraints on accretion disc viscosity inferred from changes of disc structure with time and from disc flickering distributions. The radial run of the disc viscosity parameter in four cases are presented and discussed.

Keywords: cataclysmic variables - dwarf novae - accretion discs - optical - time-series photometry - individual: V2051 Ophiuchi, HT Cassiopeia, V4140 Sagitarii, UU Aquarii.

1 Context

Accretion discs are cosmic devices where angular momentum and gravitational energy are extracted from matter by an anomalous, still unknown viscosity mechanism, allowing it to be accreted onto a central star (Frank, King & Raine 2002). Currently, the most promising explanation for the disc viscosity is related to magneto-hydrodynamic (MHD) turbulence in the differentially rotating disc gas (Balbus & Hawley 1991). From the observational standing point of view, because the properties of steady-state discs are largely independent of viscosity, one must turn to observations of time-dependent disc behavior in order to obtain quantitative information about disc viscosity. Here we adopt the prescription of Shakura & Sunyaev (1973) for the accretion disc viscosity, $\nu = \alpha_{\rm ss}\, c_{\rm s}\, H$, where $\alpha_{\rm ss}$ is the non-dimensional viscosity parameter, $c_{\rm s}$ is the local sound speed and H is the disc scaleheight. Non-magnetic[1] Cataclysmic Variables (CVs) are excellent sites for studies of disc viscosity, because of their well constrained binary environment and because their accretion discs are usually the dominant light source at UV and optical wavelengths. In particular, the subclass of Dwarf Novae (DNs) show recurrent outbursts in which their discs brighten by factors 20-100 as a consequence of mass and angular momentum redistribution on timescales of a few days. DN outbursts are explained in terms of either a thermal-viscous disc-instability (DIM, Lasota 2001) or a mass-transfer instability (MTIM, Bath 1975). DIM predicts matter accumulates in a low viscosity disc ($\alpha_{\rm cool} \sim 10^{-2}$) during quiescence, whereas in MTIM the disc viscosity is always high ($\alpha \sim 10^{-1}$). Therefore, measuring α of a quiescent disc is key to infer which model is at work in a given DN.

2 Flickering in CVs: A Short Review

Flickering are the intrinsic brightness fluctuations on timescales of seconds to dozens of minutes seen in light curves of T Tau stars, mass-exchanging binaries and active galactic nuclei (Bruch 2000 and references therein). The first step in understanding what causes flickering is to find out where is comes from. Clues for the location of the flickering sources in CVs come from the analysis of eclipsing systems.

In U Gem, flickering is stronger at orbital hump maximum and disappears during the eclipse of the bright spot (BS) – where the mass transfer stream hits the outer edge of its accretion disc. These results led to the conclusion that flickering in this DN arises at the stream-disc impact region, because of either unsteady mass inflow (Warner & Nather 1971) or post-shock turbulence (Shu 1976). On the other hand, the flickering in HT Cas disappears during eclipse of the central source and recovers well before the egress of its BS (Patterson 1981), indicating that it originates in the inner disc regions or at the WD-disc boundary layer (BL). Possible explanations for this disc+BL flickering include MHD turbulence + convection (Geertsema & Achterberg 1992), unsteady WD accretion (Bruch 1992) or events of magnetic reconnection at the disc atmosphere (Kawagushi et al. 2000).

A series of extensive optical flickering studies along the 90's (Bruch 1992, 1996, 2000) strengthened the idea that there are two different sources of flickering in CVs: in objects with strong anisotropic emission from the BS the BS-stream flickering component dominates, whereas the disc-BL flickering component prevails in objects where emission is mostly from the accretion disc.

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[1] White dwarf (WD) surface magnetic fields $B_{\rm wd} < 10^5\,G$.

The power density spectra (PDS) of flickering sources show a characteristic power-law behaviour at higher frequencies ($\propto f^{-n}$), with indexes ranging $n = 1 - 2$, and a flat slope below a cut-off frequency, $f_{\rm c}$ (Bruch 1992). The values of n and $f_{\rm c}$ vary from one object to the other and for the same object at different brightness levels (Fig. 1).

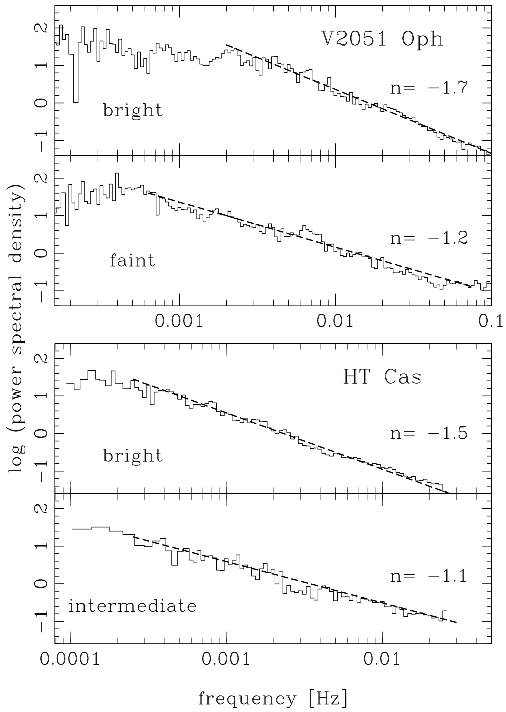

Figure 1: Optical (B-band) power density spectra for V2051 Oph (top) and HT Cas (bottom) at two different brightness levels in their quiescent states (differences between *bright, intermediate*, and *faint* are 1-2 orders of magnitude lower than differences between outburst and quiescence). Dashed lines show the best-fit power-law in each case; the corresponding power-law index n is depicted in each panel.

3 Estimating the $\alpha_{\rm ss}$ Parameter

3.1 Time changes in disc structure

By measuring the (viscous) timescale $t_{\rm v} = r/v_{\rm r} \simeq r^2/\nu \simeq r^2/(\alpha_{\rm ss}\, c_{\rm s}\, H)$ with which the disc responds to changes in mass input rate (Frank et al. 2002), one might infer a spatially-averaged disc viscosity parameter $\alpha_{\rm ss}$,

$$\alpha_{\rm ss} \simeq \frac{r}{c_{\rm s}\, t_{\rm v}} \left[\frac{H}{r}\right]^{-1} \tag{1}$$

where $v_{\rm r}$ is the viscous radial drift speed. Application of this time-lapse mapping technique to accretion discs of DN in outburst lead to $\alpha_{\rm ss} \simeq 10^{-1}$ (e.g., Baptista & Catalán 2001).

3.2 Flickering relative amplitude

Geertsema & Achterberg (1992) investigated the effects of MHD turbulence in an accretion disc. They found that the convection of turbulent eddies lead to large fluctuations in the energy dissipation rate per unit area at the disc surface $D(r)$, which could be a source of flickering in CVs and X-ray binaries. Encouragingly, the PDS of these fluctuations resemble those of flickering sources, with a power-law dependency of similar index range and the flat slope at low-frequencies. Perhaps more important, their model gives a direct relation between the energy dissipation rate fluctuations and the disc viscosity parameter, providing an interesting observational way to infer the local accretion disc viscosity – by measuring the relative amplitude of the energy dissipation rate/flickering.

In this model, the number of turbulent eddies that contribute to the local fluctuation is,

$$N(r) = 4\,\pi \frac{r}{H} \left(\frac{H}{L}\right)^2 , \tag{2}$$

where L is the size of the largest turbulent eddies. The local rms value of the fluctuations $\sigma_{\rm D}(r)$ in the average energy dissipation rate per unit area $\langle D(r)\rangle$ is given by,

$$\sigma_{\rm D}(r) \simeq 2.5\,\langle D(r)\rangle / \sqrt{N(r)}\,, \tag{3}$$

while the disc viscosity parameter can be written as,

$$\alpha_{ss} = \frac{3\,\nu_t}{2\,c_s\,H} \simeq 0.9 \left(\frac{L}{H}\right)^2 , \tag{4}$$

where ν_t is the local disc viscosity. If the disc-related flickering is caused by MHD turbulence, it is possible to infer $\alpha_{\rm ss}$ from the relative flickering amplitude, $\sigma_{\rm D}/\langle D\rangle$,

$$\alpha_{ss} \simeq 0.23 \left[\frac{r}{50\,H}\right] \left[\frac{\sigma_{\rm D}(r)}{0.05\,\langle D(r)\rangle}\right]^2 . \tag{5}$$

In the thin disc limit ($H \ll r$), disc regions with flickering amplitudes of a few percent already lead to large local $\alpha_{\rm ss}$ values ($\geq 10^{-1}$). In this scenario, CVs with highly viscous accretion discs are expected to show significant disc flickering component.

How can we measure $\sigma_{\rm D}/\langle D\rangle$? From a large, uniform ensemble of light curves of a given CV it is possible to separate the steady-light component, low- and high-frequency flickering amplitudes as a function of binary phase, to derive corresponding maps of surface brightness distributions from their eclipse shapes and, thereafter, to compute the radial run of the relative amplitude of the disc flickering component (flickering mapping, see Baptista & Bortoletto 2004).

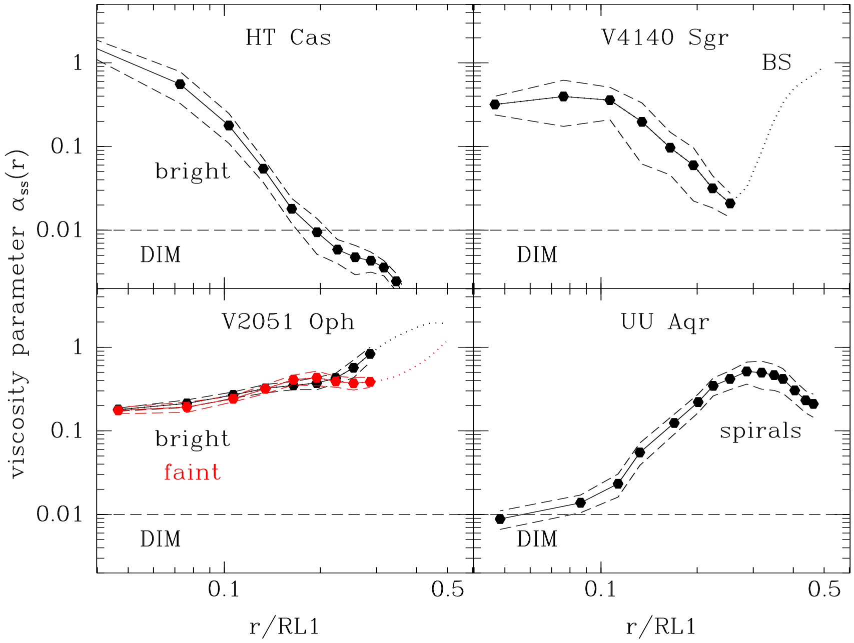

Figure 2: The radial run of the disc viscosity parameter inferred from disc flickering relative amplitude distributions, for three strong flicker DNs and for the nova-like variable UU Aqr. Dots with solid line show average $\alpha_{\rm ss}$ values, while dashed lines indicate their 1-σ limits. Horizontal dashed lines depict the typical $\alpha_{\rm cool} = 10^{-2}$ value expected for quiescent DN discs according to DIM.

4 Results and Discussion

Baptista et al. (2011) analyzed an extensive data set of optical light curves of HT Cas. Their observations frame a 2 d transition from a low state (largely reduced mass transfer rate) back to quiescence, allowing the application of both time-lapse and eclipse mapping techniques to estimate $\alpha_{\rm ss}$ and to compare the independently derived results. They find that, in the low state, the gas stream hits the disc at the circularization radius $r_{\rm circ}$, and the accretion disc has its smallest possible size. The disc fast viscous response to the onset of mass transfer, increasing its brightness and expanding its outer radius at a speed $v \simeq +0.4\,km\,s^{-1}$, implies $\alpha_{\rm ss} \simeq 0.3 - 0.5$. The newly added disc gas reaches the WD at disc centre soon after mass transfer recovery (~ 1 d), also implying a large disc viscosity parameter, $\alpha_{\rm ss} \simeq 0.5$. Flickering mapping reveal a minor BS-stream flickering component in the outer disc, and a main disc flickering component the amplitude of which rises sharply towards disc centre, leading to a radial dependency $\alpha_{\rm ss}(r) \propto r^{-2}$, and to large values $\alpha_{\rm ss} > 10^{-1}$ for $r < r_{\rm circ}$ (Fig. 2) – in agreement with the time-lapse results.

A similar analysis was performed for the DN V4140 Sgr (Baptista et al. 2012). Standard eclipse mapping in quiescence indicate that the steady-light is dominated by emission from an extended disc with negligible contribution from the WD, suggesting that efficient accretion through a high-viscosity disc is taking place. Flickering maps show an asymmetric source at disc rim (BS-stream flickering) and an extended central source (disc flickering) several times larger in radius than the WD at disc centre. Unless the thin disc approximation breaks down, the relative amplitude of the disc flickering leads to large $\alpha_{\rm ss}$'s in the inner disc regions ($\simeq 0.15 - 0.3$), which decrease with increasing radius.

Flickering mapping of the DN V2051 Oph reveals that the low-frequency flickering arises mainly in an overflowing gas stream and is associated with the mass transfer process. The high-frequency flickering originates in the accretion disc and has a relative amplitude of a few percent, independent of disc radius and brightness level, leading to large $\alpha_{\rm ss} \simeq 0.1 - 0.2$ at all disc radii (Baptista & Bortoletto 2004).

In UU Aqr, optical flickering arises mainly in tidally-induced spiral shocks in its outer disc (Baptista & Bortoletto 2008). Assuming that the turbulent disc model applies, its disc viscosity parameter increases outwards and reaches $\alpha_{ss} \sim 0.5$ at the position of the shocks, suggesting that they might be an effective source of angular momentum removal of disc gas. Since $\alpha_{\rm ss}$ increases by two order of magnitude with increasing radius, it is not surprizing that Dobrotka et al. (2012) were not able to reproduce the observed PDS of UU Aqr with a turbulent disc model of constant $\alpha_{\rm ss}$.

5 Summary and Future Steps

The picture that emerges from flickering mapping experiments of three DNs and of the nova-like variable UU Aqr underscores earlier results, indicating that there are mainly two sources of flickering in CVs: the stream-disc impact region in the outer disc and a turbulent inner accretion disc, the relative importance of which varies from system to system.

In combination with an MHD turbulent disc model, flickering mapping provides a powerful probe of accretion disc viscosity by allowing one to derive the local magnitude and the radial run of $\alpha_{\rm ss}$ from the distribution of the disc flickering relative amplitude.

The large $\alpha_{\rm ss}$ values found for the three quiescent DNs are critical for the outburst mechanism dispute. They are at odds with DIM and indicate that the outbursts of a group of DN (strong flickers) are powered by mass-transfer instabilities. Two questions related to this result seem to demand further theory development. The first one is why (and how) mass transfer from the donor star in CVs is unstable? The second one is what is responsible for the difference between the low-viscosity discs of quiescent DIM-driven dwarf nova and the high-viscosity discs of their MTIM-driven counterparts? A good first step towards solving this problem might be asking the related question of what is the influence of the WD magnetic field on the radial distribution of $\alpha_{\rm ss}$ (e.g., see Bisikalo 2014)?

An important test of the MHD turbulent disc model still to be done is to perform a flickering mapping experiment on a bona-fide DIM-driven DN to check whether it has a low-viscosity accretion disc (as predicted by DIM) and if $\alpha_{\rm ss}$ is independent of radius (as generally assumed by DIM).

Acknowledgement

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DISCUSSION

JOHN CANNIZZO: What is the theoretical expression used in determining α_{ss} from the speed of the cooling front?

RAYMUNDO BAPTISTA: Inferences of α_{ss} from time-lapse mapping of outbursting DNs are generally based on measurements of the speed of the heating wave during rise, instead of the cooling wave. [NOTE ADDED: Bobinger et al. (1997) adopted the expression $\alpha_{\rm cool} = v_{\rm cool}/c_{\rm s}$ to estimate the disc viscosity parameter from their measured speed of the cooling wave $v_{\rm cool}$. This expression lead to α values smaller than derived from Eq. (1) by a factor (H/r).]