Flickering in Black Hole Accretion discs

M. Mayer and J.E. Pringle

Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK

Abstract. We present an extension of the King et al. [1] model for the flickering of black hole accretion discs by taking proper account for the thermal properties of the disc.

First we develop a one-dimensional, vertically averaged, one-zone model for an optically thick accretion disc and study the temporal evolution. This limits the current model to the so-called high/soft state, where the X-Ray spectrum is dominated by a thermal black-body component.

Then we couple this disc model to the flickering process as described in King et al. [1]. Thus we consider the evolution of a poloidal magnetic field subject to a magnetic dynamo. By comparing to observations of X-Ray binaries in the high-soft state, we can constrain the strength of the energy density of the poloidal magnetic field to a few percent of the energy density of the intrinsic disc magnetic field.

Keywords: Magnetohydrodynamics and plasmas, Accretion and accretion disks, Black holes, X-ray binaries, Quasars; active or peculiar galaxies, objects, and systems

PACS: 95.30.Qd, 97.10.Gz, 97.60.Lf, 97.80.Jp, 98.54.-h

INTRODUCTION

Accretion powered X-Ray binaries, on both the galactic (AGN - Active galactic nuclei) and stellar scale, display significant aperiodic variability [for the latest review, see 3].

Power density spectra (PDS) of X-Ray binaries show that most variability is created on timescales of about seconds and longer. This is evident by a $v^{-1}$ behaviour of the PDS at low frequencies and a break to a steeper slope at frequencies above a few Hz. This is incompatible with the predominant timescales close to the black hole where most of the luminosity, i.e. variability, is released. Moreover, in the standard disc picture, variability created further out is damped on the viscous timescale long before it reaches the inner part of the disc where it would be observable.

Thus the origin of this variability is not well understood. There are however more statistical relations characterising this variability. Uttley and McHardy [4] finds a linear relationship between the rms variability and the flux of the source. Maccarone and Coppi [5] added higher-order statistics by introducing a characteristic shape of the so-called bicoherence.

Uttley et al. [6] give a comprehensive summary of these and other statistical properties and a test of several theoretical models against the observed quantities of the flickering variability. They rule out many models and are left with a class of models proposed by Lyubarskii [7]. He suggests that uncorrelated fluctuations in the viscosity parameter $\alpha$ (as defined in Shakura and Sunyaev [8]) on about the viscous timescale can reproduce the observed shape of the power density spectra.

King et al. [1] use this phenomenological model to fill in a physical picture. They consider the temporal evolution of a poloidal magnetic field that changes on about the
dynamical timescale according to magnetic dynamo theory and is subject to induction and radial advection. Although the timescale for the change of the magnetic field locally is connected to the dynamical timescale, they are able to reproduce the observed timescales for flickering in X-Ray binaries. They use the result of Livio et al. [9] who find that the poloidal magnetic field in neighbouring cells is sufficiently aligned on a timescale of $2R/H$ times the dynamical timescale, where $R$ is the radial distance from the black hole and $H$ the local scale height of the disc. This timescale is fairly long for geometric thin ($H/R \ll 1$) discs. If there happens to be such an alignment, then magnetic torques will enhance the accretion flow and eventually launch an large-scale inflow. This then might eventually create a disk wind/outflow.

**OUR MODEL**

While the King et al. [1] model already reproduces the statistical properties of the flickering, it contains a number of simplifications: First, they use $H/R =$const. Thus they do not account for the vertical structure of the accretion disc. While $H/R =$const. is a good approximation in the gas pressure dominated regime, in the radiation pressure dominated regime $H$ becomes constant. Moreover, $H/R$ certainly will be a function of time and radius, if there are limit cycles present.

Secondly, since their discs are very thin ($H/R = 0.08$), they use a fairly high value for the maximum allowed energy density of the poloidal magnetic field. They typically use a ten times larger value than the local intrinsic magnetic field energy density.

We started to extend this model to account for a more realistic vertical structure and to trace the thermal and viscous evolution of these discs in the presence of the flickering mechanism. We introduce the basic physical ingredients of the model below here but refer the reader to Mayer and Pringle [2] for more information on the details of the numerical implementation.

As mentioned before, the flickering in the King et al. [1] model is produced locally by a magnetic dynamo process which through reconnection can drive an enhanced mass inflow at times. The dynamoes operate in grid cells of a characteristic width $\Delta R \approx H$. Hence in cases where $H/R$ is no longer constant, we need to have a grid which adapts to the changing conditions. We therefore implemented a one-dimensional self-adaptive grid (a type of 1D adaptive mesh refinement). The AMR is written that if a refinement/coarsening occurs, both the mass, energy, angular momentum and magnetic flux is conserved.

Furthermore we introduced a time-dependent energy equation. This equation is complemented by the condition of hydrostatic equilibrium to account for the vertical structure. The poloidal magnetic field creates a magnetic torque which influences the viscous evolution of the disc. For the magnetic torque we take the average of the magnetic field in neighbouring cells to account for the reconnection process, i.e. we only get a large magnetic torque, if the magnetic field is sufficiently aligned over some distance.

The disc is a optically thick but geometrically thin disc (see Shakura and Sunyaev [8]). Thus the model in the present extension is only applicable to the so-called high-soft state in X-Ray binaries, where most of the flux comes from an black-body component. This component is thought to be produced by the optically thick disc.
There are however still a few problems in this standard accretion disc picture. All models of accretion discs using the standard model of an optically thick disc produce limit cycles (i.e. periodic variations in the luminosity) which occur on much shorter timescales than actually observed. The only source with limit-cycle behaviour on timescales comparable to theoretical models is GRS1905+105. All other sources vary on much longer timescales.

For our analysis we thus only take the high-luminosity part of the light-curve as a model for the high/soft state, while we attribute the low-luminosity part to the yet physically unresolved low/hard state.

We show sample power spectra from our model in Fig. 2. Since the observed variability in this state is fairly small (the integrated rms variability is less than or around one per cent, see Mayer and Pringle [2] for a review of observational results), we are able to constrain the value of the maximum allowed energy density of the poloidal magnetic field to be less than a few per cent of the intrinsic magnetic field density of the disc, i.e. $\beta_S \leq 0.25$ (Note that the fraction of the magnetic field energy density is $\beta_S^2$).

The overall shape of the model power density spectra in Fig. 2 agrees very well with the general shape of observed power spectra (even in the low/hard state, although then the amplitude is much higher). Higher-resolution power density spectra however show more features than just the flat part at low frequencies and then the decline to higher frequencies. Pottschmidt et al. [10] show that the power density spectrum of Cyg X-1 can be well modelled by a number of broad Lorentzian components. This "fine-structure" certainly contains more information about the internal structure of the accretion flow.
FIGURE 2. Power density spectra for a 10 M$_\odot$ black hole accreting at 0.5 $M_{\text{Edd}}$ with $\alpha = 0.1$ for different values of $\beta_S$, the strength of the poloidal magnetic field compared to the intrinsic magnetic field of the disc (Fig. 13 of Mayer and Pringle [2]).

CONCLUSIONS

We present an extension to the model for the flickering of black hole accretion disc of King et al. [1]. Since we take proper account of the vertical structure and trace the thermal evolution of the disc, we are able to constrain the energy density of the poloidal magnetic field to be less than a few per cent of the intrinsic magnetic field density of the disc. This result, however, strongly depends on the geometric structure of the accretion flow in this state.

Our model now can be extended to model the low/hard state variability as well. Then the X-Ray spectrum shows a powerlaw behaviour. This powerlaw is thought to be produced in an optically thin corona above an beneath the accretion disc. To what extent or if at all the optically thick accretion disc then is truncated at some radius, is still rather uncertain and yet has to be explored.

REFERENCES

1. A. R. King, J. E. Pringle, R. G. West, and M. Livio, MNRAS 348, 111–122 (2004).
2. M. Mayer, and J. E. Pringle, MNRAS 368, 379–396 (2006), astro-ph/0601663
3. R. A. Remillard, and J. E. McClintock, ArXiv Astrophysics e-prints (2006), astro-ph/0606352
4. P. Uttley, and I. M. McHardy, MNRAS 323, L26–L30 (2001).
5. T. J. Maccarone, and P. S. Coppi, MNRAS 336, 817–825 (2002).
6. P. Uttley, I. M. McHardy, and S. Vaughan, MNRAS 359, 345–362 (2005), astro-ph/0502112
7. Y. E. Lyubarskii, MNRAS 292, 679–+ (1997).
8. N. I. Shakura, and R. A. Sunyaev, A&A 24, 337–355 (1973).
9. M. Livio, J. E. Pringle, and A. R. King, ApJ 593, 184–188 (2003).
10. K. Pottschmidt, J. Wilms, M. A. Nowak, G. G. Pooley, T. Gleissner, W. A. Heindl, D. M. Smith, R. Remillard, and R. Staubert, A&A 407, 1039–1058 (2003).