New Astronomy 58 (2018) 84–89

Contents lists available at ScienceDirect

New Astronomy

journal homepage: www.elsevier.com/locate/newast

Modeling the response of a standard accretion disc to stochastic viscous fluctuations

Naveel Ahmad[a,*], Ranjeev Misra[b], Naseer Iqbal[a,b], Bari Maqbool[a], Mubashir Hamid[a]

[a] Department Of Physics, University of Kashmir, Srinagar 190006, India
[b] Inter-University Center for Astronomy and Astrophysics, Post Bag 4, Ganeshkhind, Pune 411007, India

HIGHLIGHTS

- The time-lag between the inner accretion rate variability with respect to that of the perturbation radius, depends on the time-period of the oscillation.
- The effect of perturbation is multiplicative in the inner regions, so the variability is stronger in the inner region than in the outer.
- The power spectra of the accretion rate in the inner regions has a power-law form.

ARTICLE INFO

Article history:
Received 22 June 2017
Accepted 27 July 2017
Available online 28 July 2017

Keywords:
Accretion
Accretion discs
Instabilities
Hydrodynamics
Methods: Numerical
X-Rays: Binaries

ABSTRACT

The observed variability of X-ray binaries over a wide range of time-scales can be understood in the framework of a stochastic propagation model, where viscous fluctuations at different radii induce accretion rate variability that propagate inwards to the X-ray producing region. The scenario successfully explains the power spectra, the linear rms-flux relation as well as the time-lag between different energy photons. The predictions of this model have been obtained using approximate analytical solutions or empirically motivated models which take into account the effect of these propagating variability on the radiative process of complex accretion flows. Here, we study the variation of the accretion rate due to such viscous fluctuations using a hydro-dynamical code for the standard geometrically thin, gas pressure dominated α-disc with a zero torque boundary condition. Our results confirm earlier findings that the time-lag between a perturbation and the resultant inner accretion rate variation depends on the frequency (or time-period) of the perturbation. Here we have quantified that the time-lag $t_{lag} \propto f^{-0.54}$, for time-periods less than the viscous time-scale of the perturbation radius and is nearly constant otherwise. This, coupled with radiative process would produce the observed frequency dependent time-lag between different energy bands. We also confirm that if there are random Gaussian fluctuations of the α-parameter at different radii, the resultant inner accretion rate has a power spectrum which is a power-law.

1. Introduction

Black hole X-ray binaries are powered by an accretion disc. The X-rays are emitted from the inner regions of the disc close to the black hole where the characteristic time-scales are expected to be of the order of less than seconds. Thus, it was rather surprising that the X-ray emission from these systems vary over a wide range of time-scales. It is now believed that this wide range occurs because viscous fluctuations with long characteristic time-scales occur in the outer parts of the disc and subsequently these variations propagate to the inner parts (Lyubarskii, 1997). Such a model qualitatively explains the power-law form of the power spectra of the X-ray emission. Moreover, these long time-scale fluctuations arising from large radii on propagating inwards gets superimposed on the smaller time-scale fluctuations arising there. Hence, this explains the linear positive relation between the *r.m.s* variability and the X-ray flux, that are observed in many X-ray binaries (Uttley and McHardy, 2001; Gaskell, 2004; Uttley, 2004; Uttley et al., 2005; Heil and Vaughan, 2010; Heil et al., 2011, 2012). Thus, the model provides a natural connection between the power spectra and the rms-flux relation which has been studied by several authors (e.g. Ingram and Done, 2011; Heil et al., 2012). Moreover, the same process should be acting on accreting systems such as Active Galactic Nuclei and hence in general can be used to obtain the size scale

* Corresponding author at: Department Of Physics, University of Kashmir, Srinagar 190006, India.
E-mail address: anaveel@gmail.com (N. Ahmad).

http://dx.doi.org/10.1016/j.newast.2017.07.011

of the system (Kelly et al., 2009; 2011). By modeling the observed fluctuations, it may also be possible to obtain direct constraints on the hydrodynamic structure of the accretion disc (Titarchuk et al., 2007).

Another critical aspect of the temporal behaviour of black hole X-ray binaries is that typically, the systems show hard lags such that the high energy photons are delayed relative to the soft ones. The time-lags increase logarithmically with energy and are surprisingly frequency dependent, $t_{lag} \propto f^{-0.7}$ (Nowak et al., 1999; Wilms et al., 2004). The magnitude of these lags are too large for them to be due to light crossing time-scales or due to Comptonization unless the corona is unphysically larger than 10^9 cms (Hua et al., 1999; Kroon and Becker, 2016). Instead, the propagation model provides an interpretation where if softer photons are produced at a larger radii compared to the high energy ones, there will be a time-lag between them corresponding to the time take for the fluctuation to propagate from the outer radius to the inner regions (Misra, 2000; Kotov et al., 2001). The energy and frequency dependence of these time-lags can also be explained within such a framework (Misra, 2000; Kotov et al., 2001). For many years, it has been puzzling why high accretion rate systems do not seem to be affected strongly by the radiation pressure instability (Lightman, 1974; Lightman and Eardley, 1974). The instability should have made bright black hole X-ray binaries in their soft state (when they are supposed to have a standard accretion disc) to have X-ray flux variations of several orders of magnitude over time-scales of minutes. Interestingly, the absence of such variation could be due viscous fluctuations in the disc (Janiuk and Misra, 2012).

Given the success and the potential of such a propagation model to explain many of the timing properties of black hole X-ray binaries, there have been attempts to integrate the basic idea of the model with one which can also explain the time averaged spectrum and other timing features such as Quasi-periodic Oscillations (QPOs). A popular model to explain the hard X-ray emission from these sources during the hard spectral state, is that the standard accretion disc is truncated and the inner region is a hot flow (Shapiro et al., 1976; Done et al., 2007). For such an accretion disc geometry, there have been a series of works (Ingram and Done, 2011, 2012; Ingram and van der, 2013; Rapisarda et al., 2016), which incorporate the basic effects of stochastic propagation model. Such an integrated approach, can explain the time-averaged spectra and the temporal properties such as rms-flux and time-lags arising due to propagation. The model can also explain the ~ 1 Hz QPO observed in these sources as relativistic precession of the hot flow. There is no doubt that in the future, there will be more such attempts to provide a comprehensive picture using more complex accretion geometries with the propagation model being an integral part of such an approach.

Since such generic models are complex it is natural that these initial endeavours that attempt to quantitatively explain the temporal features, include stochastic propagation in an approximate manner where it is assumed that the accretion rate varies at different radii and that the time taken for the propagation to move inwards is the local viscous time-scale. On the other hand, there are approximate analytical techniques which have been used to describe the diffusion process in the accretion flow and quantify the basic prediction of the propagating fluctuations (Lynden-Bell and Pringle, 1974; Lyubarskii, 1997; Misra, 2000; Kotov et al., 2001). For example, while Misra (2000) describes the propagation in terms of cylindrical sound waves, Kotov et al. (2001) have used the approximate Green's function formalism of Lynden-Bell and Pringle (1974) and Lyubarskii (1997). Solving the disc equations in a linearized form Psaltis and Norman (2000) have shown that any transition radius in the disc will act like a low-pass filter to such fluctuations and have argued that resonant features may cause Quasi-periodic behaviour. It is possible, however, to solve the time dependent hydro-dynamical equations with a stochastic viscosity to obtain the full global non-linear behaviour of the disc. Cowperthwaite and Reynolds (2014) simulated such a disc with global stochastic fluctuations in the viscosity and confirmed the non-linear behaviour of the *r.m.s* being proportional to the flux. They found that the accretion rate variations at frequencies lower than the local viscous frequency is coherent for different radii and hence revealing the basic idea of propagation fluctuation. They computed the expected time-lags and found that their magnitudes are smaller than the viscous time-scale and that they are frequency dependent. Further, Hogg and Reynolds (2016) performed global magneto-hydrodynamic simulation of accretion disc and confirmed that the Maxwell stresses in the low frequency regime, indeed produce fluctuations which propagate inwards. These simulation results, especially that the time-lags are a function of frequency need to be incorporated into future models which would strive to quantitatively explain the temporal behaviour of accreting systems.

In these previous works, the fluctuations have been introduced in the viscosity as inspired by magneto-hydrodynamic simulations (Hogg and Reynolds, 2016). However, in the standard α-disc model (Shakura and Sunyaev, 1973), the viscosity is parametrised by α such that the viscous stress is αP, where P is the pressure. Viscous variations can be then represented by variation in the α parameter. Such simulations have been undertaken for, e.g., to study the effect of these variations on unstable radiation pressure dominated discs (Janiuk and Misra, 2012) and to understand the effect of X-ray irradiation on the time dependent properties of the outer regions of an accretion disc (Maqbool et al., 2015). Since the nature especially the time-dependent behaviour of the turbulent viscosity is largely unknown, it is prudent to test different mechanisms by which the viscosity may fluctuate.

In this work we study the response of a gas pressure dominated standard accretion disc to viscus fluctuations at different radii and time-periods, concentrating on the temporal behaviour of the accretion rate at different radii rather than on the emergent spectrum. One of our motivation is to confirm whether the salient features, especially the frequency dependent time-lag are similar when the fluctuations are introduced in α rather than the viscous stress. More importantly, the aim is to introduce simple empirical functions which capture the radial and frequency dependence of the variability and time-lags which may then be used in models that quantitatively explain temporal features. The results obtained may perhaps be fairly generic despite the simplifying assumption of a standard gas pressure dominated disc. The expectation here is that empirical scaling laws obtained, may form the basis for more complex studies involving more complex accretion geometry and the coupling of the flow to the local radiative process.

In the next section, we list the basic time-dependent equations that describe the standard gas pressure dominated accretion disc. In §3, we study the response of such a disc to sinusoidal perturbations at different radii and with different time-periods. In §5, we introduce Gaussian stochastic perturbations at each radii and study the temporal behaviour of the inner accretion rate. In the last section, we summarise and discusses the important results of the work.

2. Time-dependent disc structure equations

Since we are interested in the long term temporal evolution of an accretion disc on viscous time-scales we assume as in the standard disc, vertical hydro-dynamical equilibrium leads to

$$P = \frac{GM\Sigma}{r^3}\frac{h}{2} \tag{1}$$

where h is the half thickness of the disc, $\Sigma = 2\rho h$ is the surface density and the pressure P is assumed to be due to gas pressure