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The physical origin of the X-ray variability scaling in accreting black holes

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Abstract. Active galactic nuclei and black hole binaries are observed to follow the same X-ray variability 'fundamental plane', defined by the characteristic variability timescale, black hole mass, and accretion rate. The physical origin of this empirical scaling relation, extending from super-massive to stellar-mass black holes, is however not definitively established yet. We suggest that the observed variability timescale is associated with the cooling timescale of electrons in the Comptonisation process at the origin of the hard X-ray emission. We obtain that the Compton cooling time remarkably reproduces the observed functional dependence on black hole mass and accretion rate. This result naturally arises from general properties of the emission process itself, and may provide a simple interpretation of the observed X-ray variability fundamental plane of accreting black holes.

Key words. black hole physics – radiation mechanisms: general – galaxies: active – X-rays: galaxies – X-rays: binaries

1. Introduction

Accreting black holes comprise two main classes: super-massive black holes in active galactic nuclei (AGN) and stellar-mass black holes in binary systems (black hole binaries, BHB). Similarities in their X-ray variability properties have been known for a long time (McHardy 2010, and references therein), and X-ray variability analysis is thought to provide constraints on the physical emission mechanisms and possibly on the nature of the underlying accretion flows.

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Quantitative analysis of X-ray variability is often performed in terms of the power spectral density (PSD). The observed power spectrum is generally modelled by power laws of the form $P_\nu \propto \nu^\alpha$, where $\nu = 1/T$ is the temporal frequency. A typical AGN power spectrum is characterised by a slope of $\alpha \sim -1$ at low frequencies (corresponding to long timescales), steepening to a slope of $\alpha \sim -2$ at higher frequencies (or equivalently short timescales). The corresponding break timescale, $T_B = 1/\nu_B$, associated with the PSD break, is considered as a characteristic X-ray variability timescale of the accreting system. The measured values of the PSD break timescales are typically of the order of ∼ days in Seyfert galaxies and fractions of seconds in black hole binaries (McHardy 2010; Gilfanov 2010), broadly consistent with a linear scaling with black hole mass.

A more quantitative scaling relation between variability timescale, black hole mass, and accretion rate has been obtained by McHardy et al. (2006). The resulting empirical scaling relation is observed to extend from super-massive black holes in AGNs down to stellar-mass black holes in binary systems, covering several orders of magnitude in black hole mass. This has led to the suggestion of the so-called 'variability fundamental plane', and has been claimed as a strong support for the scale-invariance of accreting black holes.

The characteristic timescale derived from the PSD break is thought to provide important insight into the underlying emission processes. A number of physical interpretations of the observed variability scaling have been proposed in the literature, trying to associate the observed break timescales with various physical timescales of the accretion disc. Although the PSD break is usually interpreted in the framework of accretion disc models, the disc itself cannot account for the hard X-ray emission component of accreting black holes, and other interpretations may also be considered.

2. Compton cooling

Hard X-ray emission is generally attributed to Compton processes (Titarchuk 1994), in which soft seed photons are up-scattered to higher energies by energetic electrons. It is thus interesting to consider physical timescales associated with the X-ray emission process itself that can be compared with the observed X-ray PSD break timescale (Ishibashi & Courvoisier 2012).

The power emitted by a single electron in the inverse Compton scattering is given by

$$L_C = \frac{4}{3} c \sigma_T \gamma^2 \beta^2 u_\gamma \,. \tag{1}$$

The Compton cooling time, which sets the characteristic timescale for the cooling of electrons by inverse Compton emission, is defined as

$$t_C = \frac{E_e}{L_C} \,, \tag{2}$$

which in the non-relativistic limit leads to

$$t_C \cong \frac{3 m_e c}{8 \sigma_T} \frac{1}{u_\gamma} \,, \tag{3}$$

where $u_\gamma = \frac{L_s}{4\pi R^2 c}$ is the radiation density at distance R, and L_s is the seed photon luminosity.

Assuming that seed photons are generated in the radiatively efficient accretion process ($L_s = \eta \dot{M} c^2$, $\eta \sim 0.1$), and expressing the radial distance in units of the Schwarzschild radius ($R = \zeta R_S$, with $R_S = \frac{2GM_{BH}}{c^2}$), we derive the Compton cooling timescale (Ishibashi & Courvoisier 2012)

$$t_C = \frac{6\pi G^2 m_e}{\sigma_T c^4} \frac{\zeta^2}{\eta} \frac{M_{BH}^2}{\dot{M}} \,. \tag{4}$$

The Compton cooling time (Eq. 4) can be considered as a characteristic X-ray timescale of the accreting system since Compton cooling is the physical process at the basis of the observed X-ray emission. The corresponding numerical values are typically of the order of ~day ($t_{AGN} \sim 0.1d$) for AGNs and ~second ($t_{BHB} \sim 0.07s$) for black hole binaries, respectively.

In particular, we note that the Compton cooling time is mainly determined by the black hole mass and the accretion rate, scaling as

$$t_C \propto \frac{M_{BH}^2}{\dot{M}} \,. \tag{5}$$

We see that the Compton cooling time is shorter for small black hole mass and/or high accretion rate. An increase in the accretion rate leads to an enhanced seed photon emission, which leads to a decrease in the characteristic timescale. On the other hand, an increase in the seed photon emission causes efficient Compton cooling of the hot corona, which in turn leads to a steepening of the Comptonised X-ray spectrum. Combining the two results, we thus expect a correlation between characteristic frequency and spectral steepening, with higher accretion rate systems having both short characteristic timescales and steep spectra.

In this picture, X-ray luminosity variations are mainly driven by electron density modulations occurring in the up-scattering medium (see also Ishibashi & Courvoisier 2009). Density modulations can be transmitted, and thus observed as luminosity variations, only if the fluctuation time is greater than the electron heating/cooling time ($t_f > t_C$); while fluctuations on timescales shorter than the electron cooling time ($t_f < t_C$) are smoothed out and effectively suppressed. The suppression of rapid fluctuations (on timescales shorter than the critical value, t_C) induces a break in the variability power spectrum, which can be associated with the observed PSD break.

3. Comparison with observations

The measured PSD break timescales in Seyfert galaxies are usually in the range ~0.01 to a few days, while the corresponding break timescales observed in black hole binaries are of the order of seconds or less (McHardy 2010; Gilfanov 2010). The numerical values of the Compton cooling time, estimated in the previous section, thus correspond to the typically measured values of the PSD break timescales in both AGNs and galactic black holes.

The empirical scaling relation between characteristic timescale, black hole mass, and accretion rate, is of the form (McHardy et al. 2006)

$$T_B \approx \frac{M_{BH}^{1.12}}{\dot{m}_E^{0.98}} , \tag{6}$$

where $\dot{m}_E = L_{bol}/L_E$ is the ratio of the bolometric luminosity to Eddington luminosity. This result is based on a main sample of 10 AGNs with a large range of accretion rates, including two galactic black holes in radio-quiet states. As the Eddington luminosity scales with the black hole mass ($L_E \propto M_{BH}$), and assuming that the bolometric luminosity is proportional to the accretion rate ($L_{bol} \propto \dot{M}$), we can re-write the observational scaling directly in terms of the physical parameters as

$$T_B \propto \frac{M_{BH}^{2.1}}{\dot{M}^{0.98}} . \tag{7}$$

Comparison of the observational scaling (Eq. 7) with our model dependence, $t_C \propto \frac{M_{BH}^2}{\dot{M}}$ (Eq. 5), shows a remarkable agreement. We thus obtain that the Compton cooling timescale precisely reproduces the observed functional dependence on black hole mass and accretion rate.

X-ray variability properties are also related to X-ray spectral features, and close couplings between the two aspects have been observed in accreting black holes. In particular, 'spectral-timing' correlations have been reported in both AGNs and black hole binaries, whereby an increase in the characteristic frequency is associated with a steepening of the X-ray spectrum (Gilfanov et al. 1999; Revnivtsev et al. 2001; Papadakis et al. 2009). Such correlations can be naturally interpreted in the framework of the above discussed Comptonisation scenario, and we may at least qualitatively account for the observed 'spectral-timing' relation.

4. Discussion and conclusion

Different physical interpretations of the observed X-ray variability scaling have been proposed and discussed in the literature. The observed PSD break timescales have been initially compared with characteristic timescales of the inner accretion disc, including orbital, thermal, and viscous timescales. For typical AGN parameters the dynamical or orbital time is of the order of ~hours, and thus too short compared to the typical break timescales measured in Seyfert galaxies; while for a standard geometrically thin disc ($H/R \ll 1$), the viscous time (of the order of ~years) result to be much too long. We note that all the physical timescales of the accretion disc are proportional to the black hole mass, and thus the approximate linear scaling of the characteristic timescale with mass is easily obtained; however the dependence on the accretion rate is less obvious, and cannot be simply accounted for in this framework.

The currently favoured interpretation is based on the so-called 'inner propagating fluctuations' model (Lyubarskii 1997; Churazov et al. 2001), in which accretion rate fluctuations originating at different outer radii propagate inwards, leading to modulations at inner radii and hence to variations in the observed X-ray flux. In this picture, the geometrically thin and optically thick accretion disc is assumed to be truncated at some distance from the centre, with the inner region being replaced by a hot optically thin flow. The PSD break timescale is then associated with a characteristic timescale, usually the viscous time, at the truncation radius of the disc. At high accretion rates the disc extends down to the last stable orbit, while at low accretion rates, the disc is truncated far away from the centre. Variations in the break timescales are then interpreted as variations in the location of the disc truncation radius. Once the disc reaches the last stable orbit, a further decrease in the characteristic timescale can only be obtained by varying the disc thickness parameter. Therefore, combining variations of the disc truncation radius and disc thickness parameter one may qualitatively account for the observed trend with the accretion rate.

We suggest another possibility, and associate the PSD break timescale with the cooling timescale of electrons in the Comptonisation process at the origin of the observed hard X-ray emission (Ishibashi & Courvoisier 2012). In our picture, the characteristic timescale is given by the Compton cooling time in both AGNs and galactic black holes, suggesting that the underlying emission mechanism is scale-invariant. Moreover, if the characteristic X-ray variability timescale is indeed set by the Compton cooling time, this may provide further support to the hypothesis attributing hard X-ray emission to Comptonisation processes in both classes of accreting black hole systems. In particular, we obtain that the Compton cooling timescale directly leads to the empirical scaling relation, naturally reproducing the functional dependence on black hole mass and accretion rate. It is interesting to note that the observational scaling simply derives from general properties of the emission process itself, and that this result is independent of the details of any specific accretion model.

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