MAGNETIC FLARES AND OUTFLOWS FROM STRUCTURED ACCRETION DISC CORONAE

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Abstract

We present a model for magnetic structured coronae above accretion discs. On the shortest timescales, spatially and temporally correlated coronal flares can explain X-ray temporal and spectral variability observed in Seyfert galaxies. In particular, power density spectra, flux-spectral index and flux-variance correlations are naturally accounted for by the model. More dramatic spectral variations (i.e. state transitions in GBHC) are associated with parameters varying on longer timescales, such as accretion rate, coronal strength or geometry of the inner disc. In the framework of the standard Shakura–Sunyaev accretion disc theory, here we discuss why energetically dominant coronae at low accretion rates are ideal sites for launching powerful MHD driven outflows. Then, if the outflow is radiatively inefficient, then so is the source overall, even without advection being relevant for the dynamics of the accretion flow. This could be an alternative scenario for LLAGN and GBHC in their low/hard state, and may have consequences for our understanding of the accretion history of the universe.

Key words: accretion, accretion discs - black hole physics - magnetic fields

1. Introduction

The hard X-ray spectra, the properties of the reflection features and of rapid time variability in accreting black holes can all be considered as indications of the presence of a structured, hot, optically thin component in the inner part of the accretion flow (the corona), situated above a cold, geometrically thin, disc. Many models of the accretion disc corona have been proposed in recent years, which are able to fit the observed time averaged spectra in terms of Comptonization of soft photons in the hot corona. However, many uncertainties regarding the actual geometry of the inner accretion flow remain unsolved (see Done 2001 for a review). Here we present a model for a structured, magnetic corona above a standard, geometrically thin and optically thick disc, that can satisfy observational constraints on both long and short time variability of these systems.

Let us briefly sketch the overall energetics of an accretion disc-corona system. The total power released by the accreting gas is defined as \( L = \dot{m} L_{\text{Edd}} = 4\pi G M m_p c \sigma_T \). To be fairly general, we assume that the coronal power generated by the disc (which is a fraction \( f \) of the total: \( L_c = f \dot{m} L_{\text{Edd}} \)) can be either dissipated locally to heat the corona, and ultimately radiated away as hard X-rays with a luminosity \( L_H = (1 - \eta)f L_c \), or used to launch an outflow with power \( L_j = \eta f L_c \). The main characteristic of our model are the following: in the hot corona the energy is stored in a strong, highly intermittent magnetic field (amplified in the turbulent disc and buoyantly expelled in the vertical direction). Magnetic energy dissipation occurs at the smallest end of the turbulent-energy cascade. Such small flares heat the corona (with a power \( L_H \)) and can trigger an avalanche in their immediate neighborhood (Poutanen & Fabian 1999), creating a bigger active region, and producing the observed flares in the lightcurves. In Sec. 2 a stochastic model (the so-called thundercloud model, Merloni & Fabian, 2001, MF1) of the short-time variability is discussed.

On longer timescales, variations of the fraction of power released into the corona, \( f \), and of the fraction of coronal power used to launch an outflow, \( \eta \), may be associated, for example, to changes of the accretion rate and/or of the geometry of the inner disc. In Sec. 3 we show that, under reasonable assumptions on the nature of the disc viscosity, the strength of the corona \( f \) increases as the accretion rate decreases. Also we discuss reasons why an energetically dominant corona can be the site where powerful outflows are produced.

2. Short timescales: magnetic flares

Seyfert 1 galaxies show strong temporal variability in the X-ray band, with a Power Density Spectrum (PDS) characterized by a “red noise” power-law: \( P(f) = Af^{-\alpha} \) with \( \alpha \sim 1.5 \) (see e.g. Nandra, 2001). The dynamical timescale of such systems, \( t_{\text{dyn}} = 9 \times 10^9 \beta^{3/2} (M_{\text{BH}}/10^8 M_\odot) \) s, is such that good time-resolved spectroscopy can directly provide information about the heating mechanism of the corona. In fact, from the observational point of view there is a growing evidence that during a flare the X-ray spectrum becomes softer as the (2-10 keV) flux increases (see e.g. Vaughan & Edelson 2001). Also, a remarkable linear...
correlation between variability and flux on all timescales has recently been reported (Uttley & McHardy 2001).

The coronal magnetic field intensity depends on the dissipation rate and on the field geometry. Here we assume, on the basis of the strong spectral and temporal variability, that the corona is patchy and the magnetic field concentrated in a number of small active regions where dissipation occurs (Haardt, Maraschi & Ghisellini 1994; Stern et al. 1993; Di Matteo, Celotti & Fabian 1999).

We assume that the luminosity of an active region is determined by the size of the avalanche, and therefore scales as the size of the region: \( L(R_a) = C_1 R_a^0 \). Due to the fractal nature of reconnection and avalanche generation, we also assume that the number of active regions of size \( R_a \) at any time, is given by \( dN(R_a)/dR_a = C_2 R_a^{-p} \). The PDS slope, \( \alpha \), is then related to the indices \( D \) and \( p \) by the relation \( p = 2D + 3 - \alpha \). The constants \( C_1 \) and \( C_2 \) can be fixed imposing the overall normalization for the total corona covering fraction and the average hard luminosity (see MF1 for details). The covering fraction \( C \) is related to the total variability level as illustrated in the example in Fig. 1.

![Figure 1. Average PDS of ten segments of a simulated lightcurve (each 3 \times 10^4 seconds long), for fixed coronal optical depth, \( \tau = 1.5 \) and \( D = 1 \). From bottom to top the different curves correspond to a covering fraction \( C = 0.03 \) (orange, open circles), 0.01 (purple, open squares), 0.005 (cyan, open triangles), 0.002 (blue, filled stars), 0.001 (green, filled circles), 0.0003 (red, filled squares) and 0.0001 (black, filled triangles). On the right, close to each curve, the corresponding fractional rms is reported.](image_url)

As discussed in MF1, we have simulated AGN X-ray lightcurves fixing \( \alpha = 1.5 \) (in order to reproduce the observed properties of the PDS), and studied the time and spectral variability properties of the model.

We assume that the X-ray spectrum is produced by thermal Comptonization in each spherical active region of size \( R_a \), lifted above the disc at a height \( H_a \) and with Thomson optical depth \( \tau \). The active regions illuminate the cold disc; part of the flux is reflected and part is absorbed and reprocessed. We assume that most of the accretion power is dissipated in the corona \( (f > 0.7) \), so that reprocessed radiation is the main source of soft photons in the active regions. For large and luminous active regions the amount of soft radiation intercepted by an active region increases, and the spectrum is softer. This is illustrated in the example of Fig. 2.

We calculate the spectrum using an analytic approximation for thermal Comptonization (see MF2), fixing \( H_a = H_S = 2GM_{BH}/c^2 \), and we study the correlations between spectral properties and total luminosity (in the 3-10 keV band). We have fixed \( M_{BH} = 10^7 M_\odot \) and an accretion rate of 10% of the Eddington one. In MF1 we show in detail how such a model can reproduce the observed luminosity - spectral index correlation. In the following section, instead, we will focus on the luminosity-variability correlation (see also Merloni 2001).

### 2.1. The Luminosity-variability correlation

Recently, Uttley & McHardy (2001) have discovered a remarkable linear correlation, on all timescales (Uttley, private communication), between variability and flux in many compact accreting systems.

We have analysed one of our simulated lightcurves in order to look for a similar correlation. With the parameters \( D \) and \( C \) fixed to the values of 1 and 0.001, respectively, we have produced a lightcurve of the total duration of about 3 \times 10^6 s, with resolution of 1 minute.

Then, keeping fixed the time resolution, we calculated mean and variance for segments of different length. The results, binned in luminosity intervals, are shown in Fig. 3, where the length of the segments \( T \) is measured in minutes. The variance corresponds to the integral of the PDS shown in Fig. 4 from frequencies \( 1/(T \times 60) \) to 1/60 (Hz).

A clear correlation is evident in all cases, consistent with a linear one with an offset. Uttley & McHardy (2001) argues that the correlation rules out any possible shot noise model. Still, we are able to reproduce it within our thundercloud model, which is indeed a generalized shot noise model. One possible explanation for this lies in the way the lightcurve is ‘randomized’. Once the average covering fraction \( C \) and the distributions indexes \( D \) and \( p \) are fixed, the total expected number of active region at any time \( N_{tot}(t) \) is calculated, then the actual (randomized) number, \( \hat{N}_{tot}(t) \), is picked from a poissonian distribution that has \( \hat{N}_{tot}(t) \) as its mean. Then, starting from the smallest flares, we calculate in similar fashion the number of active regions of every size in such a way as to ensure that their total is exactly \( N_{tot}(t) \). Therefore, random variations in \( N_{tot}(t) \) (which correspond to random variations in the covering fraction \( C \)) are transferred to flares of all sizes, and of all timescales, thus enforcing a correlation between the overall flux level and the amount of variability on all time-scales. This merely reflects the fact that large
Figure 2. The inner corona is mapped into a square. For simplicity, we chose $D = 2$, so that the pixels have equal luminosity, and the total luminosity scales with the covered area. The region of the corona active at any time are represented by filled squares, whose size is distributed as a power-law, with index $p = 2$. Each region is assumed to have the same height above the disc ($H_a = R_S$) and optical depth ($\tau = 1$). The color code shows the spectral index of the filled active regions, calculated self-consistently taking into account thermal Comptonization of disc photons (both intrinsic and reprocessed) and of synchrotron emission in the active regions themselves (see MF1). It ranges from $\Gamma = 1.62$ (pink) to $\Gamma = 2.21$ (red). Clearly the more luminous state (right hand side, for which the instantaneous covering fraction is larger), is dominated by active regions with soft spectra.

Figure 3. Luminosity dependence of the variance calculated for segments of a simulated lightcurve ($D = 1$, $C = 10^{-3}$ and $\tau = 1.5$) with a fixed temporal resolution of 60 seconds. The duration of the different segments (in minutes) is written in each panel. The fitting functions are of the form $\sigma = k(L_{3-10} - L_0)$, with $k$ and $L_0$ constants.

active regions are indeed made of a collection of correlated microflares (avalanches).

3. Long timescales: low-luminosity systems

On timescales much longer than the dynamical one, the system evolution is regulated by the global properties of the accretion flow. Here we want to discuss the implication of our coronal model for the long-term properties of systems accreting at low rates (as compared to the Eddington one). In particular we will consider Galactic Black Hole Candidates (GBHC) in their low/hard state and the so-called Low Luminosity AGN (LLAGN). These two classes of systems have many common features: GBHC have very weak (or absent) quasi-thermal spectral component in the soft X-ray/EUV spectral range; hard (photon index $\Gamma = 1.6 - 2$) X-ray power-law spectra, rolling over at $\sim 100$ keV (evidence of thermal Comptonization in a optically thin medium); compact (unresolved) flat or inverted radio core, probably extending to the NIR or optical regime and a clear temporal correlation between the radio and hard X-ray fluxes. LLAGN, in turn, show a remarkable weakness of the Big Blue Bump (Ho 1999); hard X-ray spectra ($\Gamma = 1.6 - 1.8$); compact radio cores nearly ubiquitously, often accompanied by ‘jet-like’ features; radio spectra with turnover frequencies of the order $\sim 0.1 - 100$ GHz and radio loudness anti-correlated with accretion rate (for nearby ellipticals with reliable mass estimates; Ho 2002).

All these observational evidences suggest that outflows are common features of low $\dot{m}$ systems with hard X-ray spectra.
3.1. CORONA DOMINATED ACCRETION DISCS

As shown in Merloni & Fabian (2002, MF2), if angular momentum transport in a standard, geometrically thin and optically thick accretion disc is due to magnetic turbulent stresses, the magnetic energy density and the effective viscous stresses inside the disc are proportional to the geometric mean of the total (gas plus radiation) and gas pressure:

\[ \frac{B^2}{8\pi} = P_{\text{mag}} \simeq \alpha_0 \sqrt{P_{\text{tot}} P_{\text{gas}}}, \]  

(1)

with \( \alpha_0 \) constant (of the order of unity).

Then, the fraction of gravitational power \( f \) released in a magnetic corona increases as the accretion rate decreases, because the disc is more and more gas pressure dominated even in its inner parts. When the disc is completely gas pressure dominated (at accretion rates smaller than the critical value \( \dot{m}_{\text{crit}} \sim 0.1(\alpha_0 M_{\text{BH}}/M_\odot)^{-1/3} \)), the strength of the corona depends on the poorly understood mechanisms of vertical flux tube transport in the disc, but it is likely that \( f > 0.7 \) (see MF2 for a more thoroughly discussion).

3.2. MHD JETS FROM MAGNETIC CORONAE

The magnetic energy density in the corona is given by

\[ \frac{B^2}{8\pi} = \frac{3L_H}{4\pi R_a^2 N_{\text{tot}} c^4} \left( \frac{c}{v_{\text{dis}}^2} \right), \]  

(2)

where \( v_{\text{dis}} \) is the dissipation velocity and depends on the uncertain nature of the reconnection process (MF1), and can be assumed to be of the order \( v_{\text{dis}} \sim 0.01c \).

Models and simulations of jet production (Blandford & Znajek 1977; Meier 1999) show that it is the poloidal component of the magnetic field which mainly drives the production of powerful jets, and the output power can be expressed as (Livio, Ogilvie & Pringle 1999)

\[ L_j = \frac{B^2}{8\pi} 2\pi R_{\text{cor}}^2 R_{\text{cor}}^2 \Omega. \]  

(3)

Here \( R_{\text{cor}} \) is the size of the region where most of the coronal power is dissipated and \( \Omega \) is the typical angular velocity of the magnetic field lines.

If \( H_a \) is the typical coronal flux tube scaleheight (height of a reconnection site), we have \( B_p/B \simeq H_a/R_{\text{cor}} \), and therefore

\[ L_j = \frac{3}{2} L_H \left( \frac{c}{v_{\text{dis}}} \right) \left( \frac{H_a}{R_{\text{cor}}} \right)^2 \left( \frac{R_{\text{cor}} \Omega}{c} \right) \]  

(4)

which in turn gives, for the fraction of corona power that goes into the MHD outflow

\[ \eta = \left( 1 + \frac{2}{3} \frac{v_{\text{dis}}}{c} \left( \frac{R_{\text{cor}}}{H_a} \right)^2 \left( \frac{c}{R_{\text{cor}} \Omega} \right) \right)^{-1}. \]  

(5)

By inspection of Eq. (3) we can conclude that the outflow power is stronger if the coronal scaleheight is large with respect to the distance from the central source. This would help in increasing the relative strength of the poloidal component of the magnetic field, that is the one ultimately responsible for the powering of the jet.

As an example, for \( v_{\text{dis}} \simeq 0.01c \), \( R_{\text{cor}} \sim 7R_S \), \( H_a \sim 2R_S \) and \( \Omega = \Omega_K(R_{\text{cor}}) \), we obtain \( \eta_{\text{MHD}} \simeq 0.55 \): the MHD jet can carry away a substantial fraction of the coronal power.

4. CONCLUSIONS

We have presented a model to explain spectral and temporal variability on the smallest timescales in the X-ray emission from Seyfert Galaxies and GBHC. We have simulated X-ray light-curves that reproduce the observed PDS properties and the spectral variability. The basic geometric properties of the corona we propose are the following:

- The corona must not be uniform, but structured and heated intermittently (flares);
- The spatial and temporal distribution of the flares are not random, but proceed in correlated trains of events (avalanches);
- The size of the avalanches determines the size of the active regions, which are distributed as a power-law; larger avalanches are more luminous and have softer spectra.

On longer timescales, the evolution of the corona is governed by the evolution of the accretion rate and/or of the inner disc geometry. At low accretion rate, the strength of a magnetic corona produced by buoyant magnetic flux tube amplified in an underlying standard accretion disc increases. If the energy in the corona, as we suggest, is stored in the magnetic field, and the height of a reconnection site is much larger than its size, which is of the order of the disc thickness, powerful MHD outflows can be launched from the inner corona.

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