Microquasars in the low/hard state: strong coronae, compact jets, and the high frequency variability

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Abstract. We apply a model of magnetically dominated coronae above standard accretion discs to the low/hard state of galactic black holes. When the disc-corona coupling is accounted for self-consistently assuming that magneto-rotational instability is at work in the disc, and that the corona is generated by buoyant escape of disc magnetic structures, then the model predicts powerful, X-ray emitting coronae at low accretion rates. A main consequence is discussed: the possibility that the corona itself is the launching site of powerful, MHD driven jets/outflows. This depends crucially of the coronal scaleheight. Finally, we present the first radial profiles of a corona at different accretion rates, and discuss their implications for high frequency variability.

1. Introduction

In [1] we have shown how it is possible to build a physically self-consistent model for an accretion disc corona: assuming that the turbulent magnetic stresses generated by MRI are responsible for angular momentum transport in the disc, and that the field saturates mainly due to buoyancy (as should be the case if strong coronae are to be generated), then the fraction of power released into the corona as a function of radius, \( f(R) \), can be uniquely determined by solving the algebraic equations for accretion disc structure. For uniform discs (which may not be the case in the radiation pressure dominated parts, see [4]), we have

\[
f(R) \simeq \sqrt{\alpha} \left( 1 + \frac{P_{\text{rad}}(R)}{P_{\text{gas}}(R)} \right)^{-1/4},
\]

where \( \alpha \) is a constant of the order of unity and \( P_{\text{rad}} \) and \( P_{\text{gas}} \) represent radiation and gas pressure in the disc, respectively.

A major consequence of such a disc-corona coupling, which is of interest in the context of microquasars, is that coronae are more powerful at low accretion rates, in particular below the critical rate at which the radiation pressure dominated part of the disc disappears altogether. Indeed, if the \( \alpha \) viscosity parameter is high enough, \( f \) can approach unity, and we are therefore left with a flow in which most of the energy goes into the magnetically dominated corona. The cold, geometrically thin disc, although very dim, may manifest itself as a reprocessor of X-ray coronal radiation. This makes our solution different from a simple magnetically dominated non radiative accretion flow (NRAF): the two may be distinguished, for example, by the presence of relativistically smeared reflection features.
2. MHD outflows from powerful coronae

A magnetically dominated corona, with magnetic flux tubes corotating with the underlying disc at nearly Keplerian speed, $v_{\text{Kepp}}$, is prone to generate powerful MHD outflows. Let us examine in some detail the disc-corona-outflow energetics. At a distance $R$ from the center, the (magnetic) energy flux emerging from the disc is

$$Q_c(R) = f(R)Q(R) = \frac{3GM\dot{M}f(R)}{8\pi R^3} \text{ ergs cm}^{-2} \text{s}^{-1},$$  \hspace{1cm} (2)$$

Part of this energy will be dissipated in reconnection events, heating the coronal plasma that is then cooled by inverse Compton scattering soft photons. Such energy flux will emerge as hard X-rays, and can be parametrized as $F_H(R) = (1 - \eta)Q_c(R)$, where $\eta$ is in general a function of the distance. The remaining fraction of the coronal magnetic energy flux is carried off by the jet/outflow: $Q_j(R) = \eta Q_c(R)$. Most models of MHD generated outflows from rotating systems agree on the conclusion that the final power carried by such jets depends on the poloidal component of the magnetic field and on the angular velocity of the field lines. We have therefore $dL_j = \xi 2\pi RQ_j(R)dR = (B_p^2/8\pi)dA_c\Omega R$, where $dA_c \equiv 2\pi RdR$ is the element of disc area covered by the corona (which has a covering fraction $\xi$) and the poloidal component of the coronal magnetic field is a function of the corona scaleheight, $H_c$ (the height of a reconnection site, from which the outflow is launched): $B_p \simeq B(H_c/R)$. The intensity of the coronal magnetic field, in turn, depends on how quickly the field dissipates $B^2 = \frac{8\pi Q_c(1-\eta)}{\xi v_{\text{diss}}}$. Combining the expressions for $dL_j$ and $B$, we obtain

$$\eta = \left(1 + \xi \left(\frac{R}{H_c}\right)^2 \frac{v_{\text{Kepp}}(R)}{v_{\text{diss}}}\right)^{-1}. \hspace{1cm} (3)$$

The fraction of coronal power that is channeled in a MHD jet/outflow, depends crucially on the height of a reconnection site (or, more generally, on the scale-height of the magnetically dominated corona).

3. Radial profiles

Most of the variability of black hole binaries (both the broad band one and the QPOs) can be spectrally associated to the hard component. Moreover, QPO frequencies tend to correlate with various X-ray spectral parameters; in particular with those sensitive to the system size. In general, higher frequencies are associated to softer spectra. In principle, if a magnetic corona is responsible for generating (or amplifying) the observed modulation of the hard X-ray flux, and the corona is vertically extended (large $H_c$), both radial and vertical oscillation may be observed. This implies that both the radial and vertical size of the corona play an important role in shaping the Power Density Spectra of these sources. For example, if jet and corona are coupled systems, as we envisage, QPO properties (in particular their amplitude and narrowness) are bound to be influenced by the jet. Indeed, shows that when the microquasar GRS 1915+105 is in a hard state characterized by strong radio emission (states $\chi_1$ and $\chi_3$ according to the classification of), the high frequency noise component in the PDS is strongly
suppressed as compared to the hard states that do not show radio emission (states $\chi_2$).

Radial profiles of coronal emissivity and of the fraction of the total gravitational power channeled either into coronal heating or into an outflow, should be derived in order to build more physical models for the QPO mechanism. As a final goal, time dependent versions of such models should be implemented. Here we present a simple, illustrative example of a possible calculation. We have fixed the free parameters $\xi = 0.5$ and $c/v_{\text{diss}} = 30$. The coronal optical depth is fixed at $\tau = 0.8$ (variation of this parameters affect the slope of the X-ray spectrum but not the overall energetics), and the temperature is calculated self-consistently from the heating-cooling balance (including both coronal synchrotron and disc radiation fields as sources of soft photons for Comptonization) as in [10], at every annulus of width $dR$. The most critical assumption is that regarding the radial profile of the coronal scaleheight $H_c$, for the influence it has in determining the fraction of power that goes into the jet. In general, the coronal scaleheight will be larger for a larger value of $f$ (because more strongly buoyant flux tubes should rise more) and proportional to the number of twists a coronal loop, placed at a distance $R$ and with footpoints separated by a distance $dR$, experience due to the disc differential rotation that torques the flux tube. Also, it should have a power-law dependence on the distance due to the natural disc flaring. In summary, we may write $H_c/R \propto R^p f(R) d\ln \Omega/dR = Af(R) R^{p-1}$, with $0 < p < 1$. In our calculations, we chose $p = 1/2$ and $A = 1$.

Once the accretion rate is fixed, we can integrate the disc structure equations with the prescription of Eq. (1) for the coronal fraction, and solve for $f(R)$ and $\eta(R)$. With the solution in hand, we can calculate the intensity of the magnetic field in the corona as a function of $R$ and then compute the amount of energy flux that is converted locally into hard X-rays, into soft quasi thermal emission (including both intrinsic and reprocessed disc emission), into self-absorbed synchrotron radiation and into jet-power. In Figure 1 we show the solutions for a 10 $M_\odot$ black hole accreting at $\dot{m} = 0.005$ (typical low/hard state accretion rate, thick lines) and at $\dot{m} = 0.25$ (thin lines).

At low accretion rates, the hard X-rays from the corona dominate over the quasi-thermal disc radiation. In the innermost region of the corona the energy density of the synchrotron radiation field dominates over the external disc one, and coronal heating produces strong, highly variable IR/Optical non-thermal emission. The kinetic power channeled into the jet is the main repository of the gravitational energy of the accretion flow in the inner 10 Schwarzschild radii. At high accretion rates the inner part of the disc is radiation pressure dominated, the corona is strongly suppressed, and no strong outflow is generated, as expected.

4. Conclusions

If a standard, geometrically thin and optically thick accretion disc is coupled to a corona through buoyancy of magnetic flux generated by MRI in the disc itself, then a powerful corona is generated whenever gas pressure dominates over radiation pressure, i.e. at low accretion rates. This implies that microquasar in the low/hard state may be characterized by strong coronae on top of very dim, cold discs, that may be seen only as reprocessors. Depending on the detailed coronal geometry, and in particular on its vertical extent, low accretion rate systems may produce strong MHD driven jets/outflows whose total kinetic energy flux may exceed the radiated one. Beside their radio emission, such outflows should manifest themselves through their influence on the variability properties (noise
Figure 1. The differential luminosity from an annulus of the accretion disc corona system $dL = F(R)2\pi R dR$ as a function of the distance $R$, for different components: hard X-rays (due to inverse Compton scattering in a hot corona, solid lines), soft X-rays/UV (intrinsic and reprocessed disc emission, dashed lines), self-absorbed synchrotron emission in the IR/Optical band (dot-dashed lines) and total kinetic jet power (dotted lines). Thick lines correspond to an accretion rate of $\dot{m} = 0.005$, thin lines to $\dot{m} = 0.25$.

and QPOs), for example reducing the intensity and narrowness of such timing features. In order to understand the complex interplay between coronal physics and dynamics and the variability properties of microquasars, full time- and radial-dependent models are needed. As a first illustrative step in this direction, we have shown here a stationary model for the radial profiles of the different spectral components emerging from a disc-corona system at various accretion rates.

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