Accretion disc coronae as magnetic reservoirs

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ABSTRACT
Most astrophysical sources powered by accretion onto a black hole, either of stellar mass or supermassive, when observed with hard X-rays show signs of a hot Comptonizing component in the flow, the so-called corona, with observed temperatures and optical depths lying in a narrow range ($0.1 \lesssim \tau \lesssim 1$ and $1 \times 10^9 K \lesssim T \lesssim 3 \times 10^9 K$). Here we argue that these facts constitute strong supporting evidence for a magnetically-dominated corona. We show that the inferred thermal energy content of the corona, in all black hole systems, is far too low to explain their observed hard X-ray luminosities, unless either the size of the corona is at least of the order of $10^9$ Schwarzschild radii, or the corona itself is in fact a reservoir, where the energy is mainly stored in the form of a magnetic field generated by a sheared rotator (probably the accretion disc). We briefly outline the main reasons why the former possibility is to be discarded, and the latter preferred.

Key words: accretion, accretion discs – magnetic fields

1 INTRODUCTION
A hard X-ray power-law is a common feature of most astrophysical systems powered by an accreting black hole (Zdziarski 1999, and references therein). The relative strength of the power-law component with respect to the quasi-blackbody one, due to thermal emission from an accretion disc, is used to classify the different observed spectra from different sources into two main states: the hard one (when the power-law component dominates) and the soft one (when, on the contrary, the disk blackbody component is prominent).

The vast majority of spectral studies of galactic black hole candidates (GBHC) and radio-quiet Seyfert 1 galaxies clearly suggest that the primary hard X-ray continua of these sources are produced by thermal Comptonization (Shapiro et al. 1976; Sunyaev & Titarchuk 1980; see Zdziarski 1999, and reference therein) in a hot, rarefied plasma (hereafter, the corona) which probably resides where most of the accretion energy is released, namely in the inner part of the flow. Furthermore, there is clear evidence that this hot, Comptonizing medium strongly interacts with the colder thermal component: such an interaction is not only required to explain the ubiquitous reflection features in the X-ray spectra (Lightman & White 1988; George & Fabian 1991; Matt, Perola & Piro 1991; Fabian et al. 2000, and reference therein), but could also provide the feedback mechanism that forces the observed values of coronal temperature and optical depth to lie in very narrow range for all the different observed sources (Haardt & Maraschi 1991).

Theoretically, the idea that a disc configuration could explain the nature of the power source in black hole systems was recognized as early as in 1969 (Lynden-Bell 1969), and the basic elements of what is still today considered the standard accretion disc theory were already in place in 1973 (Shakura & Sunyaev 1973; Novikov & Thorne 1973; Pringle 1981). Although successful in explaining many observed features of black hole candidates (both stellar and supermassive), standard accretion disc theory left unspecified the nature of both the angular momentum transport mechanism needed to sustain the disc in the first place, and the hot Comptonizing medium giving rise to the hard spectral component.

In recent years, it has become apparent, from both theory and numerical simulations of a fully magnetohydrodynamical accretion disc (Balbus & Hawley 1998), that the most viable process for angular momentum transport involves some kind of turbulent magnetic viscosity. The dissipation of the magnetic energy built up by the magnetorotational instability (MRI) in an accretion disc has then been shown (Miller & Stone 2000) to produce a non uniform active corona which extends a few scaleheights above the disc.

The relevance of the magnetic field for the viscosity law and the emission processes in accretion disc coronae, first introduced in a seminal paper by Galeev, Rosner & Vaiana (1979), has already been considered in detail by Burm & Kuperus (1988); Di Matteo, Celotti & Fabian (1997); Di Matteo, Blackman & Fabian (1998); Di Matteo (1998); Di Matteo, Celotti & Fabian (1999), and in Wardziński and Zdziarski (2000). They all assume that the corona is the region where a significant fraction of the total accretion power is dissipated and consequently work out the strength of the
magnetic field, and the importance of the related radiative processes (cyclo-synchrotron in particular). These are in turn compared with the observed luminosities and spectra in order to assess the viability of any such model.

The purpose of our letter, instead, is to demonstrate, with a simple energetics argument centered on the small thermal energy content of any plausible corona, that a strong magnetic field in the coronal region of black hole accretion discs (both stellar and supermassive) is required by the existing data. In particular, we show that the measured thermal energy of the Comptonizing flow is far too small to explain the observed hard X-rays luminosities without postulating that the flow is itself a magnetic reservoir: the magnetic field dominates the energy balance in the corona and act as an in situ reservoir of energy that powers the high energy emission.

2 ENERGETICS

Consider a black hole of mass \( M = mM_\odot \) and hard X-ray luminosity \( L = 1.5 \times 10^{38} f_{\mu m} \) ergs s\(^{-1}\), where \( f_{\mu m} \) is the accretion rate in units of the Eddington one and \( f_{\mu m} \) is simply the fraction of the total luminosity emitted in hard X-rays.

Observed galactic black hole candidates (GBHC) whose mass has been reliably estimated, show that, if the source is not in quiescence, the value of \( f_{\mu m} \) ranges between 0.01 and 0.1, approximately.

To be fairly general, let us consider the thermal energy content of the hot electrons in a hard emitting region of size \( R = rR_S \), where \( R_S = 2GM/c^2 \) is the Schwarzschild radius of a black hole of mass \( M \). We have

\[
E_{\text{th}} \simeq \frac{\pi \tau}{2} R^2 kT_e \simeq 5.8 \times 10^{28} r R_S^2 m_{\mu m} \mathcal{M}^2,
\]

where \( \sigma_T \) is the Thomson scattering cross section and \( T_e = T_9 \times 10^9 \) K.

Thus, for even a local equilibrium, the electrons must be heated on a timescale

\[
t_{\text{heat}} = \frac{E_{\text{th}}}{L} \simeq 3.9 \times 10^{-10} r T_{9} r^2 m_{\mu m}^{-1}.
\]

If the energy has to be supplied to the hot electrons from an external heating source, and no reservoir of stored energy is present where the the hot electrons are, then the light crossing time of such region \( t_{\text{cross}} = R/c \simeq 10^{-5} m_{\mu m} \) (which is the shortest time-scale over which energy can be transferred there) has to be shorter than the heating time. This translates into a condition on the total size of the hard X-ray emitting region:

\[
r > 2.5 \times 10^{14} \frac{f_{\mu m}}{T_9} \]

independent of the black hole mass.

For the vast majority of radio-quiet Seyfert 1s and GBHCs in their hard state, we deduce from observations that the hot flow is optically thin (0.1 \( \lesssim \tau \lesssim 1 \)) and has typical temperatures of the order of 1 \( \lesssim T_9 \lesssim 3 \) (see e.g. Gierliński et al. 1997; Poutanen & Coppi 1998; Zdziarski et al. 1998; Zdziarski 1999; Petrucci et al. 2000; Done et al. 2000), implying a typical dimension of the Comptonizing region of the order of thousands Schwarzschild radii: we have, for example, \( r > 1250 \) for the set of typical values \( \tau \simeq 0.6, T_9 = 1.6 \) (corresponding to \( kT_e \simeq 100 \) keV) and \( f_{\mu m} = 0.05 \).

Such a large coronal region is not physically plausible, for a number of reasons. First of all it is far too large to explain the fastest observed variability, both for galactic black hole candidates (see e.g. Poutanen & Fabian 1999; Macarone et al. 2000) and for AGN (Lee et al. 2000). Strongly variable emission is clearly indicative of an emission cycle made of an energy storage phase followed by an energy release phase. Thus, the corona cannot be a uniform continuous medium, unless it is geometrically thin (sheet-like; see Celotti, Fabian & Rees 1992) so that the crossing time in one direction is orders of magnitude shorter that that in the other direction. Secondly, spectral evidence of a strong reflection component and broadened iron Kx emission lines in Seyfert 1s can be explained only assuming localized hard X-rays emitting regions shining above the inner part of the accretion disc. Also, the different ratios of accretion disc (blackbody-like) to hard X-ray luminosity observed in different sources, or in the same source at different times, imply that the geometry of the coronal plasma cannot be a slab one, but is rather made up of a number of distinct active regions (Haardt, Maraschi & Ghisellini 1994). Furthermore, if the external source of energy is the underlying accretion disc, the amount of energy deposited in the corona is proportional to the local disc viscous power, which is a strong function of the radial distance and decays rapidly outwards, thus almost all the energy is concentrated in the few inner tens of Schwarzschild radii. Further spectral evidence against a uniform corona extending out to thousands of \( R_S \) for GBHC can be found in Zdziarski et al. (1998), Done & Życki (1999), Gilfanov et al. (1999).

The simplest solution to these problems is to assume that the corona is a collection of \( N \) small (\( \sim R_S \), at most) active regions, whose thermal electron energy is just a fraction of the total. We envisage the magnetic field energy \( B^2/8\pi \) as the main reservoir in the Comptonizing region. Thus, the condition \( t_{\text{heat}} > t_{\text{cross}} \) for a magnetically-dominated coronal active region, translates into a condition on the magnetic field there (see Di Matteo, Celotti & Fabian 1997):

\[
B_c > \frac{5.8 \times 10^8}{r} \left( \frac{f_{\mu m}}{f_{\text{cross}} N m} \right)^{1/2} \mathcal{G},
\]

where we have introduced the factor \( f_{\text{cross}} = v_A/c = B/\sqrt{4\pi \rho} \) in order to take into account the fact that in a magnetically-dominated active region the effective velocity for energy transfer is the Alfvén one, \( v_A \), which is, under typical coronal conditions, unlikely to exceed the value \( v_A \sim 0.3c \).

On the other hand, the strength of the magnetic field that rises buoyantly from the disc is in principle limited only by equipartition with the disc pressure (Galeev, Rosner & Vaiana 1979). Following Wardziński and Zdziarski (2000) we

\* Such a strong constraint can in principle be alleviated if, as is plausible, the total hard X-ray emitting area is divided into a number \( N \) of independent regions. However, the strong variability observed in these sources can be used to set an upper limit \( N \lesssim 10 \) (Di Matteo, Celotti & Fabian 1996; Poutanen & Fabian 1999; Wardziński & Zdziarski 2000).
calculate the maximum value of the magnetic field inside the
disc (assuming equipartition) and obtain, for the disc region

dominated by gas pressure,

\[ B_d \simeq \frac{3.4 \times 10^8 m^{3/5}}{(am)^{9/20}(1 - f_H)^{1/20}} G, \]

where \( \alpha \) is the viscosity parameter, and

\[ B_d \simeq 5 \times 10^{-7} \left[ \frac{am(1 - f_H)}{\alpha} \right]^{1/2} G \]

for a disc region dominated by radiation pressure.

To be self-consistent, we need \( B_d > B_c \), which implies, for
the two cases (gas and radiation pressure dominated
discs), respectively (note that, again, the limits below depend
only very weakly on the black hole mass)

\[ r > 1.7 f_H^{1/2} (1 - f_H)^{1/20} \alpha^{9/20} m^{-1/20} m^{1/10} (f_{\text{cross}} N)^{-1/2}, \]

and

\[ r > 11 \left( \frac{f_H (1 - f_H) \text{com}}{f_{\text{cross}} N} \right)^{1/2}. \]

As opposed to the case of a thermally dominated
corona, eq. \( \text{[6]} \), the sizes of magnetically dominated coronal
region implied by eqs. \( \text{[5]} \) and \( \text{[6]} \), are perfectly consistent
with the various spectral and temporal constraint discussed
above.

3 DISCUSSION

From the argument presented above, it should be quite clear
that the inferred temperatures and optical depths of accre-
tion disc coronae in black hole candidate systems demon-
strate that the energy content of the thermal electrons is
far too low to explain the hard X-ray luminosity of these
sources.

Nevertheless, a number of questions still remain to be
answered, which affect the estimates of the energy balance
in the hot coronal plasma. It is still controversial whether
the magnetic field is amplified in the disc up to equipartition
with the gas or the total pressure, and this controversy also
affects the nature of the disc viscosity law, with interesting
consequences for the issue of stability (see e.g. Nayakshin,
Rappaport & Melia 2000). Also uncertain is whether the
magnetic energy in a reconnection site is mainly dissipated
into electrons or protons. In the latter case, as shown by Di
Matteo, Blackman & Fabian (1997), given the low Coulomb
transfer rate between protons and electrons in the optically
thin coronal plasma, it is quite likely that the corona at
the equilibrium is a two-temperature flow (Janiuk & Czerny
2000; Rożanska & Czerny 2000). Thus, the ions could be an-
other energy reservoir, sharing with the magnetic field most
of the energy content in the corona (Di Matteo, Blackman
& Fabian 1997), and acting as mediators between the mag-
netic field and the radiating electrons. However, they would
also be likely heated to supervirial temperature in the inner
region, evaporating the accretion disc and causing the the
coronal flow to become effectively an outflow (see Meyer et
al. 2000; Spruit & Haardt 2000; Merloni et al., in prepa-
ration). In general we have to consider the possibility that
part of the energy dissipated via magnetic reconnection is
converted into kinetic energy, causing bulk motion of the

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