High-Energy Emission from Microquasars (with BH)

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Abstract The source of the high-energy emission from black holes, in the energy range observed by *INTEGRAL* and *XMM-Newton*, is a key point in the understanding of several processes occurring in black holes (i.e. as QPOs, relativistic Fe line, measurements in radio). In this paper we review the different models proposed for this high-energy emission and how these could be related with other phenomena observed in black holes. We give some insights into the results obtained from the spectral analysis of *INTEGRAL* and *XMM-Newton* data of GX 339–4.

Key words: Black hole physics – accretion, accretion discs – radiation mechanisms: non-thermal – radiation mechanisms: thermal

1 Black hole states

When BHs become into ouburst, they evolve through different states (low/hard, hard intermediate, soft intermediate, high/soft states) characterized by different spectral, timing, optical, IR and radio properties. For a recent prescription of the state classification scheme we refer to Homan & Belloni (2005) and Belloni et al. (2005). In the earlier times of this science (before 1990s) it was thought that the state evolution of a black hole was driven by $\dot{M}$ (Esin et al., 1997). But, since some states can span a large variation in luminosities it was suggested (Homan et al., 2001) that other parameter may play a role in these state transitions. This parameter could be, e.g. the coronal compactness of the high-energy emission.

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In the following, we list all the different states from the recent prescription, apart from the quiescent state in which black hole transients spend most part of their lifes.

- Low/hard state (LS): this is the state in which the outbursts begin and end. The X-ray spectrum is characterized by very low disk emission and very important high-energy emission in the form of a powerlaw with photon index in the range $\Gamma = 1.3 - 1.4$. A high-energy cut-off is usually seen (Sunyaev & Titarchuk 1980 and Grove et al. 1998), associated to the kinetic temperature of the thermal distribution of electrons in the Comptonizing corona. Sometimes, low frequency QPOs are observed. Flat-spectrum radio emission is observed, associated to a compact jet ejection (Fender et al., 2004).
- Intermediate (soft/hard) states (SIMS/HIMS): showing both bright disk and high-energy powerlaw emission components. Photon index is within the range $\Gamma = 1.5 - 2.5$. The few instances of HFQPOs appeared in the SIMS (formerly called as Very/High state). Just before the transition to the SIMS, Fender et al. (2004) suggested that the jet velocity increased rapidly, giving rise to a fast relativistic jet.
- High/Soft state (HS): the disk component is the dominant in the spectrum, with a weak powerlaw high-energy emission. No core radio emission is observed (Fender et al., 2004). Some timing properties (Wijnands et al., 1999), that were thought to be characteristic of the LH and HIMS are still present in this state, although in a much weaker form. This would suggest a common origin in the characteristics found in these states. No high-energy cut-off is observed in this state (Grove et al., 1998).

2 Source of the high-energy emission

The X/γ-ray spectra (1–1 000 keV) from black holes can be described by a soft disk emission (< 10 keV) plus a high-energy emission (> 20 keV) in the form of a powerlaw. The soft X-ray spectra often shows signatures from the inner parts of the accretion disk, such as the relativistic Fe line (6.4–6.97 keV) and the correspondent reflection bump (20–30 keV), both being different aspects of the same physical origin (i.e. fluorescence of the Fe ions and Compton back-scattering, respectively, both being the most obvious reactions of an irradiated disc by a high-energy source; George & Fabian 1991).

The high-energy emission comes from the (inverse) Comptonization of the soft photons from the inner accretion disk by a corona (consituted by electrons and positrons). Both the geometry and location of this corona are a matter of debate. In the former model (Esin et al., 1997), this corona was filling the inner regions of a truncated disk. Markoff et al. 2003, Markoff et al. 2005 showed that the base of a jet could replace an extended corona for the high-energy emission source. Independetly, Miller et al. (2006) found the existence of an inner disk in GX 339–4 during LH state from X-ray observations. All these issues can be better explained if the base of a jet is the source of hard X-ray emission. This scenario is very tempting, due to the non-thermal emission already observed in BHs during different states (Joinet et al. 2007 in the LH, Malzac et al. 2006 and Gierliński et al. 1999 in the intermediate and HS states, respectively), which could be understood as synchrotron processes occurring at the base of the jet.

We will show in the following that the base of a jet, which evolves in properties (opacity and compacticity) during the outburst, could give rise to the X/γ properties already observed in the black hole candidate GX 339–4.

3 *INTEGRAL* and *XMM-Newton* observations of GX 339–4

In Caballero-Garcia et al. (2008) we present simultaneous *XMM-Newton* and *INTEGRAL* observations of the luminous black hole transient and relativistic jet source GX 339–4. GX 339–4 started an outburst on November of 2006 and our observations were undertaken from January to March of 2007. We triggered five *INTEGRAL* and three *XMM-Newton* target of Opportunity observations within this period. Our data cover different spectral states, namely Hard Intermediate (obs. 1), Soft Intermediate (obs. 2 and 3) and High/Soft (obs. 4 and 5).

The hybrid thermal/non-thermal Comptonization EQPAIR model (Coppi , 2000) provides the injection of a non-thermal electron distribution with Lorentz factors between Γ_{min} and Γ_{max} and a powerlaw spectral index Γ_{inj}. The cloud is illuminated by soft thermal photons emitted by an accretion disc. These photons serve as seed for inverse Compton scattering by both thermal and non-thermal electrons. The system is characterized by the power (i.e. luminosity) L_i supplied by its different components. We express each of them dimensionlessly as a compactness parameter, $\ell_i = L_i \sigma_T/(R m_e c^3)$, where R is the characteristic dimension and σ_T the Thompson cross-section of the plasma. Thus, ℓ_s, ℓ_{th}, ℓ_{nth} and $\ell_h = \ell_{th} + \ell_{nth}$ correspond to the power in a soft disk entering the plasma, thermal electron heating, electron acceleration and the total power supplied to the plasma. The total number of electrons (not including e^+e^- pairs) is determined by τ_T, the corresponding Thompson optical depth, measured from the center to the surface of the scattering region. If we consider injection from pairs e^+e^-, then the total optical depth of the thermalized scattering electrons/pairs is expected to be $\tau_T \geq \tau_P$. We used the LAOR model (Laor , 1991) to model the relativistic iron line emission, with the emissivity index (β) free and tied to the opposite value of that of the EQPAIR.

Spectra and models of the five different periods have been plotted in Figure 1.

In Table 1 we show the evolution of the most important parameters inferred from the model.

The results obtained by applying EQPAIR fits to the data indicate a high value for the coronal compactness for obs. 1, but within the range of values found in the literature. For obs. 3, 4 and 5 this value is high as well (when compared to that obtained in obs. 2). We thus confirm the correlation between coronal compactness and covering fraction of the cold reflecting material by Nowak et al. (2002) for obs. 2 to 5. The high value of the coronal compactness found for obs. 1 (HIMS)

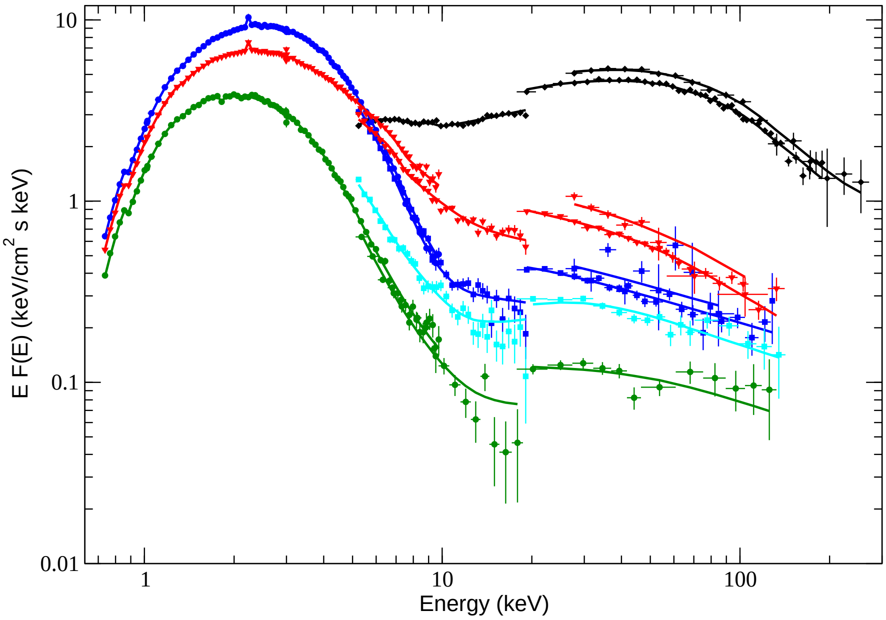

Fig. 1 Unfolded spectra from observations 1 to 5 (black, blue, red, cyan and green, respectively). The continuum line shows the fits with EQPAIR (combined with LAOR) model.

Table 1 Best-fit parameters of the joint XMM/EPIC-pn, JEM-X, ISGRI and SPI spectra for the 5 obs. Fits have been performed simultaneously with EQPAIR combined with LAOR.

Obs. number	ℓ_h/ℓ_s	ℓ_{nth}/ℓ_h	τ_p	kT_e (keV)	$[\Omega/2\pi]$
1	$3.9^{+0.6}_{-0.2}$	$0.40^{+0.15}_{-0.03}$	$2.39^{+0.15}_{-0.18}$	27.5±1.2	$0.38^{+0.06}_{-0.04}$
2	$0.05^{+0.003}_{-0.01}$	0.90±0.10	< 0.02	69±4	$0.40^{+0.3}_{-0.04}$
3	$0.28^{+0.03}_{-0.01}$	0.84±0.03	$1.41^{+0.03}_{-0.06}$	10.8±0.3	1(f)
4	$0.24^{+0.02}_{-0.005}$	$0.49^{+0.02}_{-0.01}$	2.5±0.5	4.3±0.8	1(f)
5	$0.13^{+0.01}_{-0.02}$	0.38±0.02	$0.89^{+0.04}_{-0.05}$	10.5±0.7	$0.72^{+0.16}_{-0.10}$

would indicate that the Comptonizing high-energy source is compact in size. This would be in agreement with the proposed scenario of Markoff et al. (2005), in which the base of the jet could be the source of the Comptonizing elecrons. The fact that we are detecting the thermal cut-off would be consistent with the detection of the coronal emission as well. Otherwise, for obs. 2 (SIMS), the values for both the coronal compactness and opacity found are extremely low. Moreover, the kinetic temperature found for the thermal electron distribution of the corona is very high (and close to the high-energy limit indeed). We understand them as issues indicative of the lack of coronal emission during this obsservation. During obs. 3 to 5 (SIMS), both the coronal compactness and opacity increase again (accompanied with the significant detection of a relativistic line in obs. 3), thus indicating re-appearance of the corona after obs. 2.

The claim for the disappearance of the corona during obs. 2 slightly after the detection of plasma ejection events in radio by Corbel et al. (2007) is in agreement with previous claims by Rodriguez et al. (2008) (and references therein) of same behaviour in GRS 1915+105. This behaviour could be understood as the base of the jet being the source of the high-energy emission in GX 339–4 and GRS 1915+105.

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