The high energy emission from black holes

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Abstract. The origin of the high energy emission (X-rays and γ-rays) from black holes is still a matter of debate. We present new evidence that hard X-ray emission in the low/hard state may not be dominated by thermal Comptonization. We present an alternative scenario for the origin of the high energy emission that is well suited to explain the high energy emission from GRO J1655−40.

In this study we focus on black hole transients (i.e. binary systems constituted by a star and a black hole as the compact object). These systems usually spend long time in quiescence \((L_X \approx 10^{+33}_{-33} \text{ erg/s})\) and become in outburst \((L_X \approx 10^{+37}_{-38} \text{ erg/s})\) every few years. During the outburst, spectral evolution occurs, but always beginning and ending in the low/hard state (described below).

1. The relativistic Fe Kα line

Emission below 10 keV can be due to a combination of thermal emission from the disk, and non-thermal emission from a corona. It is difficult to study disks through their continuum spectra, so the most pragmatic way to study the disk is to use broad Fe Kα emission lines. This line (as the reflection component that we will explain later) arises from the fluorescence of the inner disk from an irradiating source of high energy emission (George & Fabian, 1991). Depending on the ionization state of the disk this line is centered at 6.4–6.97 keV. From the study of the profiles of these lines, it can be inferred the spin of the black hole, which can be between zero for an Schwarzschild black hole (Fabian et al., 1989) to a maximally rotating regime in the case of a Kerr black hole (Laor, 1991). In the hard X-ray emission \((E \geq 10 \text{ keV})\) a spectral hump usually appears, called the reflection bump, with the same origin. Thus, both reflection and broad Fe Kα line should appear together during the observations. Nevertheless, both effects are inhibited when a high ionization degree occurs, because the disk becomes a perfect reflector of the γ-rays (Ross et al.1999).

Current observations of relativistic lines suggest that a range of black hole spin parameters may be seen (for reviews, see Miller 2007 and Nandra et al. 2007). It is therefore important to take relativistic effects into account by fitting spectra with the appropriate line and reflection models. Inner disks can get very close to the black hole \((d \leq 6 R_g)\) and this would imply a very concentrated source for the high energy emission, i.e., the high energy source has to be centrally compact.

2. The states of the black holes and related behaviour

In the most accepted picture for the black hole states (Tanaka & Lewin, 1995) the classification arises from the characterization of X-ray emission (usually a multicolor black body with an inner disk temperature of \(T < 1 \text{ keV}\)) and hard X-ray emission \((E \geq 20 \text{ keV})\), the last best phenomenologically described by a power-law. The high/soft state is characterized by strong disk emission \((> 25\%)\) and an steep power-law \((\Gamma > 2.4)\). The low/hard state has almost no disk emission and the power-law dominates the spectrum \((> 75\%)\). During the Steep Power Law state both disk and power-law emission are important, although \(\Gamma\) is steep. During the evolution along the outburst some transitional states appear, called intermediate (Homan & Belloni, 2005) with characteristics of both low/hard and high/soft states, depending on the case.

Grove et al.(1998), on the basis of CGRO observations, proposed that the high/soft state of black holes is associated with an unbroken powerlaw, usually understood as non-thermal origin of the high energy emission. On the other hand, the low/hard state was associated with a spectral cut-off at 100 keV (coinciding with the kinetic temperature of the thermal distribution of the -inverse-Comptonizing electrons), implying a thermal origin for the high energy emission.

3. The standard model

Sunyaev & Titarchuk (1980) proposed a thermal corona being the source of the high energy emission from black holes. Some years later, Esin et al.(1997) proposed the standard disk plus coronae model. In this model, the inner disk goes inwards while the outburst evolves from the
low/hard to the high/soft states. An advection dominated accretion flow (ADAF) corona fills the inner regions of the disk, providing the (inverse) Comptonizing electrons. The disk provides the photons to be Comptonized. This was considered to be the source of the high energy emission during the last 30 years.

However, the above mentioned model has several drawbacks. The first one is that the standard model can not explain the QPOs (Quasi Periodic Oscillations) behaviour. QPOs are the highest frequency oscillations in black holes (typically between 140 and 450 Hz) which are commensurate with Keplerian orbital frequencies at the ISCO (Innermost Stable Circular Orbit). X-rays QPOs appear in the low/hard state, are maintained in the intermediate states and are quenched in the high/soft state (see review by van der Klis, 2004). Also, there is an strong coupling between hard X-rays and radio emission, difficult to understand without taking into account hard X-ray emission from a jet. As can be seen in a recent review from Fender et al.(2004), black holes in the low/hard state show radio emission in the form of a steady jet with a low value for the Lorentz factor (Γ < 1.4). During the intermediate state the radio emission is variable and Γ is higher. In the Steep Power Law state the radio emission is optically thin with a high value of Γ > 2. In the high/soft state the radio emission is quenched. While the proposed scenario in Fender et al.(2004) would be consistent with the first point of the standard model proposed by Esin et al.(1997), the source of the high energy emission in the low/hard state is still debated. The base of jets have been proposed to be the source of the high energy emission Markoff et al.(2001), Markoff et al.(2003) and Markoff et al.(2005). Nevertheless, the model of Markoff is only dedicated to hard X-ray domain (E < 100 keV).

4. The alternative to the standard model

Coppi (1999) developed the EQPAIR hybrid thermal/non-thermal (inverse) Comptonization model. This model can explain the excess (with respect a pure thermal model) of the high energy emission already observed in black hole states during the high/soft state (E > 200 keV). The physical mechanism of this model is that (inverse) Comptonization from a hybrid thermal and non-thermal distribution of particles (leptons) is the source of the high energy emission. The most important consequences of this model are both the disappearing of high energy cut-offs when the distribution of particles is highly non-thermal and the presence of the annihilation line at 511 keV. This line results from the annihilation of relativistic $e^+e^−$ pairs in mildly relativistic and non-thermal distributed plasmas. INTEGRAL and GLAST are key missions in the detection of this line. Several attempts have been attempted to detect this line from microquasars but still there are not fiducial detections (Guessoum et al., 2006). We think that this line, if detected, would confirm the hypothesis of the source of the high energy emission being highly concentrated and relativistic. These conditions would be the typical of the base of a jet. Although this model seems to be very promising it deals only with static coronae and, as shown in Beloborodov (1999), if particles of the plasma acquire high velocities ($v/c \geq 0.2$), the high energy radiation is highly anisotropic.
5. GRO J1655−40: a particular case

GRO J1655−40 is a black hole transient discovered on 1994 July with the CGRO satellite (Zhang et al., 1994). It is a LMXB with a black hole of mass $m_{BH} = 7.02 \pm 0.22 M_\odot$ (Orosz & Bailyn, 1997). The inclination of the system is ≈70° (van der Hooft, 1998) although the inclination of the inner disk would be as high as 85°.

This system may harbor a maximal spinning black hole ($a \geq 0.9$), indicating an inner radius of $r \leq 1.4 R_g$ (Miller et al., 2005). Strong QPOs are detected (300-450 Hz) (Strohmayer, 2001) and extremely relativistic radio jets have been detected in radio (Hjellming & Rupen, 1995).

Tomsick et al. (1999) did the former detection of unbroken powerlaw emission up to 800 keV during the low/hard state. INTEGRAL observations during the 2005 outburst were done up to 500 keV during the low/hard state (Caballero-García et al., 2007). In this work, the low/hard state was modeled using both simple models like a power-law, and using EQPAIR. The lack of a break in fits with the simple power-law implies that non-thermal Comptonization may dominate the hard X-ray spectrum. Additional modeling with EQPAIR confirms that non-thermal Comptonization is best able to explain the observed spectrum. This work suggested thermal Comptonization processes not being the main source for the high energy emission of GRO J1655−40. However, more work is needed to disentangle the source of the high energy emission, and INTEGRAL observations are planned for a broad sample of black hole transients.

References

Beloborodov, A. M., 1999, ApJ, 510L, 123B
Caballero-Garcia, M. D., Miller, J. M., Kuulkers, E., Diaz Trigo, M., Homan, J., Lewin, W. H. G., Kretschmar, P., Domingo, A., Mas-Hesse, J. M., Wijnands, R., Fabian, A. C., Fender, R. P. & van der Klis, M., 2007, ApJ, 669, 534
Coppi, P. S., 2000, Bulletin of the American Astronomical Society, 32, 1217
Esin, A. A., McClintock, J. E. & Narayan, R., 1997, ApJ, 489, 865
Fabian, A. C., Rees, M. J., Stella, L., White, N. E., 1989, MNRAS, 238, 729
Fender, R. P., Belloni, T. M. & Gallo, E., 2004, MNRAS, 355, 1105F
George, I. M. & Fabian, A. C., MNRAS, 1991, 249, 352
Grove, J. E., Johnson, W. N., Kroeger, R. A. et al., 1998, ApJ, 500, 899
Guissoum, N., Jean, P. & Prantzos, N., 2006, A&A, 457, 753G
Homan, J. & Belloni, T., 2005, Ap&SS, 300, 107H
Hjellming, R. M., & Rupen, M. P., 1995, Nature, 375, 464
Laor, A., 1991, ApJ, 376, 90
Markoff, S., Falcke, H. & Fender, R., 2001, A&A, 372, 25
Markoff, S., Nowak, M., Corbel, S., Fender, R. & and Falcke, H., 2003, A&A, 397, 645
Markoff, S., Nowak, M. A., Wilms, J., 2005, ApJ, 635, 1203M
Miller, J. M., Fabian, A. C., Nowak, M. A. & Lewin, W. H. G., 2005, The Tenth Marcel Grossmann Meeting. On recent developments in theoretical and experimental general relativity, gravitation and relativity
Miller, J. M., ARA&A, vol. 45
Nandra, K., O’Neill, P. M., George, I. M. & Reeves, J. N., 2007, astro-ph/0708.1305, accepted for publication in MNRAS
Orosz, J. A., Bailyn, C. D., 1997, ApJ, 477, 876
Sunyaev, R. A. & Titarchuk, L. G., 1980, A&A, 86, 121S
Strohmayer, T. E., 2001, ApJ, 552, L49
Ross, R. R., Fabian, A. C., Young, A. J., 1999, MNRAS, 306, 461
Tanaka, Y., Lewin, W. H. G., 1995, Black-hole binaries, In : Lewin, W. H. G., van Paradijs J., van der Heuvel, E. P. J., (Eds.), X-ray Binaries, Cambridge University Press, Cambridge, 308-330
Tomsick, J. A., Kaaret, P., Kroeger, R. A. & Remillard, R. A., 1999, ApJ, 512, 892
van der Hooft, F., Heemskerk, M. H. M., Alberts, F., & van Paradijs, J., 1998, A&A, 329, 538
van der Klis, M., 2004, astro-ph/0410551, to appear in Compact stellar X-ray sources, Lewin & van der Klis (eds), Cambridge University Press
Zhang, S. N., Wilson, C. A., Harmon, B. A., Fishman, G. J., Wilson, R. B., Paciesas, W. S., Scott, M., & Rubin, B. C., 1994, IAU Circ. 6209