Black Hole States: Accretion and Jet Ejection

Belloni T.

INAF-Osservatorio Astronomico di Brera, Via E. Bianchi 46, I-23807 Merate, Italy

Abstract. The complex spectral and timing properties of the high-energy emission from the accretion flow in black-hole binaries, together with their strong connection to the ejection of powerful relativistic jets from the system, can be simplified and reduced to four basic states: hard, hard-intermediate, soft-intermediate and soft. Unlike other classifications, these states are based on the presence of sharp state transitions. I summarize this classification and discuss the relation between these states and the physical components contributing to the emitted flux.

INTRODUCTION

Since the launch of RossiXTE, our knowledge of the high-energy emission of Black Hole Binaries (BHB) has increased enormously, leading to a new, complex picture which is difficult to interpret. At the same time, a clear connection between X-ray and radio properties has been found (see Fender 2005). In the following, I present briefly the state paradigm that is now emerging, based on a large wealth of RossiXTE data from bright transient sources and its connection with jet ejection (see Belloni et al. 2005; Homan & Belloni 2005; Fender, Belloni & Gallo 2004). I discuss this in general terms, in the attempt to simplify the picture as much as possible.

BLACK HOLE STATES AND JET EJECTION

The results of detailed timing and color/spectral analysis of the RossiXTE data of bright BHBs have evidenced a very wide range of phenomena which are difficult to categorize. Nevertheless, it is useful to identify distinct states. Based on the variability and spectral behavior and the transitions observed in different energy bands, we consider the following states in addition to a quiescent state (see Homan & Belloni 2005; Belloni et al. 2005; Casella et al. 2004,2005 for the description of the different QPO types):

- Low/Hard State (LS): this state is associated to relatively low values of the accretion rate, i.e. lower than in the other bright states. The energy spectrum is hard and the fast time variability is dominated by a strong (~30% fractional rms) band-limited noise. Sometimes, low frequency QPOs are observed. The characteristic frequencies detected in the power spectra follow broad-range correlations (see Belloni, Psaltis & van der Klis 2002). In this state, flat-spectrum radio emission is observed, associated to compact jet ejection (see Gallo, Fender & Pooley 2003; Fender, Belloni & Gallo 2004).

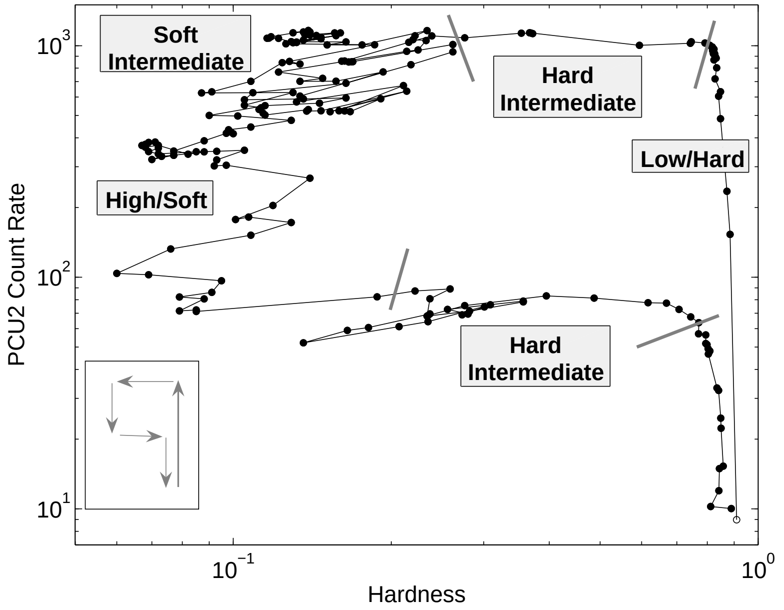

FIGURE 1. Hardness-Intensity diagram of the 2002/2003 outburst of GX 339-4 as observed by the RXTE PCA. The gray lines mark the state transitions described in the text. The inset on the lower right shows the general time evolution of the outburst along the 'q'-shaped pattern. From Belloni et al. (2005).

- Hard Intermediate State (HIMS): in this state, the energy spectrum is softer than in the LS, with evidence for a soft thermal disk component. The power spectra feature band-limited noise with characteristic frequency higher than the LS and usually a rather strong 0.1-15 Hz type-C QPO (see e.g. Casella et al. 2005). The frequencies of the main components detected in the power spectra extend the broad correlations mentioned for the LS. The radio emission shows a slightly steeper spectrum (Fender, Belloni & Gallo 2004). Just before the transition to the SIMS (see below), Fender, Belloni & Gallo (2004) suggested that the jet velocity increases rapidly, giving origin to a fast relativistic jet.
- Soft Intermediate State (SIMS): here the energy spectrum is systematically softer than the HIMS. The disk component dominates the flux. No strong band-limited noise is observed, but transient type-A and type-B QPOs, the frequency of which spans only a limited range. No core radio emission is detected.
- High/Soft State (HS): the energy spectrum is very soft and strongly dominated by a thermal disk component. Only weak power-law noise is observed in the power spectrum. No core radio emission is detected (see Fender et al. 1999; Fender 2005).

This simplified classification needs to be supported by a picture of the time evolution in a transient source. The states described above are defined also in terms of their transitions, which need to be taken into account. A sketch of the evolution of the 2002/2003 outburst of GX 339-4 is ideal to show these transitions (see Homan & Belloni 2005; Belloni et al. 2005). Figure 1 shows the outburst in a Hardness-Intensity Diagram

(HID): the x-axis shows the X-ray hardness and the y-axis the detected count rate (from Belloni et al. 2005). The outburst can be described in the following way.

- The system starts its outburst as a weak hard source (the bottom right in the HID): the first detection with the RXTE/PCA (a factor of $\sim$10 lower than the first point in Fig. 1), indicates an X-ray flux a factor of $\sim$10 higher than in quiescence (Homan et al. 2005). The flux increases with time, while the X-ray colors indicate that the spectrum is still hard and only mildly softening: the source moves upward in the right branch. During this period, the infrared flux was seen to correlate strongly with the X rays, indicating that both components are connected, possibly originating from a jet (Homan et al. 2005). This branch corresponds to the LS, when flat-spectrum radio emission is observed (see Fender et al. 1999; Fender, Belloni & Gallo 2004). The characteristic frequencies of the different noise components in the power spectrum increase with time. The energy spectrum is roughly described by a cutoff-power law.
- At the top of the right branch, GX 339-4 moves left and enters a horizontal branch, corresponding to the HIMS. The transition is shown by the dotted line. The precise position of this line corresponds to a marked change in the IR/X correlation (Homan et al. 2005). The drifting to the left is the result of two causes: the appearing of a thermal disk component and the steepening of the power-law component. In GRS 1915+105, recent Integral/RXTE observations (Rodriguez et al. 2004) indicate that in this state two hard components are at work (see also Zdziarski et al. (2001). In the power spectra, the characteristic frequencies continue to increase so that the transition in the timing domain appears to be rather smooth. As GX 339-4 moves left in the HID, the radio spectrum steepens slightly and as the source approaches the ‘jet line’ (see below) the velocity of the jet outflow increases (Fender, Belloni & Gallo 2004).
- When the source, moving left, passes the second dotted line, a very sharp transition is observed. The variation of X-ray hardness is small, indicating that the energy spectrum does not change by a large amount. However, the power spectrum changes abruptly: the strong band-limited noise and type-C QPO disappear and a sharp type-B QPO appears. The source has entered the SIMS. After this transition, the source remains for a long time in the upper left quadrant. The spectrum is soft and dominated by the thermal disk component, and the power spectrum shows complex and variable features. Transient type-B QPOs are observed, but always when the hardness is comparable to that of the first detection. The sharp transition, observed in other systems as well (see Homan & Belloni 2005; Casella et al. 2004) corresponds to the crossing of the ‘jet line’ (in the terminology of Fender, Belloni & Gallo 2004). It is in correspondence to the crossing of the jet line that the strong radio flare is observed (Gallo et al. 2004) and a fast relativistic jet is launched. This is also observed in other systems such as GRS 1915+105, XTE J1859+226 and XTE J1550-564.
- After entering the SIMS, the source remains for a long time (about five months) in the upper left quadrant, moving in a complex fashion (see Fig. 1). The spectrum is soft and dominated by the thermal disk component, and the power spectrum shows very complex and varying features. Transient type-B QPOs are observed,

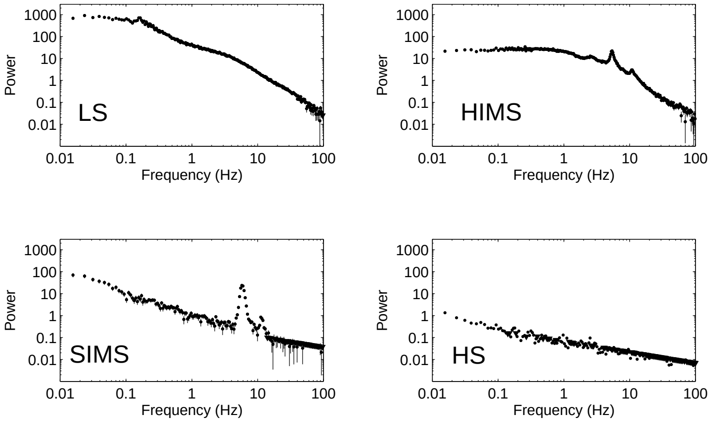

FIGURE 2. Examples for power spectra of GX 339-4 corresponding to the four states described in the text (adapted from Homan & Belloni 2005).

as well as other weak features. However, no strong band-limited noise component is observed. The properties of the SIMS are complex, and in other systems such as XTE J1859+226 fast transitions to and from the HIMS (i.e. between type-A/B and type-C QPOs) are observed (Casella et al. 2004), corresponding to the crossing of the jet line. For that source, there is evidence that subsequent radio flares are observed in correspondence of these transitions (see Casella et al., this volume). During the SIMS, observed radio emission corresponds only to the previous jet ejections (Fender, Belloni & Gallo 2004).

- Once the count rate of GX 339-4 goes below a few hundred counts per second per PCU, it enters the HS. The spectrum remains soft, the flux decreases with time, and the power spectrum only features a weak power-law component. Even integrating all the HS observations, no other timing component appears. No radio emission is observed in the HS (see Fender 2005).
- Below $\sim$100 cts/s/PCU, the source hardens again and enters the HIMS (third dotted line in Fig. 1). Notice that for three observations the source is found back in the range of hardness corresponding to the HS, and indeed HS properties are observed at those times in the power spectrum. No clear instance of SIMS is seen, although one observation at hardness similar to the bright SIMS points does show a clear 1 Hz QPO which could be a low-frequency version of the type-B ones, which were observed around 6-7 Hz at high flux.
- As GX 339-4 continues to harden, it moves back to the LS with a smooth transition. The points in the HID reach almost the same position where they started the outburst.

This picture, albeit simplified, provides a useful framework within which one can work on a modeling of the properties of the accretion flow and the ejection of collimated jets. This classification differs from that proposed by McClintock & Remillard (2005), being based on the presence of sharp state transitions rather than on a characterization in terms of spectral and timing parameters.

PHYSICAL STATES

In order to understand the scheme outlined above, we should consider the main components that are observed from the system.

Spectral components

There is amounting indication that three main spectral continuum components contribute to the observed high-energy flux (I deliberately ignore additional components such as emission lines and Compton reflection). The first is the thermal thin disk, observed at energies below 10 keV. This component is probably present in the LS, but its temperature is in most cases too low to be observable (see e.g. the case of XTE J1118+480; Frontera et al. 2001; McClintock et al. 2001). In the HIMS it contributes a small (varying) degree to the X-ray flux, while it is dominant it in the SIMS and the HS. This component appears to be rather quiet and does not contribute much to the observed fast variability. There is evidence that the innermost radius of this thin disk, as evaluated from the energy spectrum, decreases from large values in the LS to smaller values in the HS, although absolute measurements of this radius are plagued by a number of problems (see e.g. Merloni, Fabian & Ross 2000).

The second component is much harder and is usually fitted with a thermal Comptonization from $\sim$100 keV electrons or with its approximation as a power-law with a high-energy cutoff. This is the component that is observed in the LS and which is clearly associated to the strong band-limited noise typical of this state. In recent years, the possibility that this component originates directly from the jet has been proposed and fits to the broad-band spectra of LS sources have been attempted (see e.g. Markoff et al. 2003). It is not observed in the HS.

The third component is modeled with a steep power law, observed in the HS and which has been reported also for a variety of spectra the state attribution of which is uncertain (see Grove et al. 1998) but in some cases probably corresponding to the HIMS. This component was detected in GRS 1915+105, which is always observed in the HIMS (Zdziarski et al. 2001) and attributed to non-thermal Comptonization. For the SIMS, there is some evidence that no high-energy cutoff is observed with HEXTE, indicating that this component is present (Homan et al., in prep.). Interestingly, Integral/RXTE observations of GRS 1915+105 reported by Rodriguez et al. (2004) show that the combined timing/spectral properties can be explained with the simultaneous presence of both hard components, one with a high-energy cutoff and one without. Therefore, the scenario that is emerging for the high-energy component is one with a thermal component in the LS and a non-thermal one in the HS, while in the HIMS, which is intermediate between these two, both components are present. It is therefore possible that in the top branch in Fig. 1 (HIMS) the thermal hard component decreases and the non-thermal hard component appears, although it is not clear how gradual these changes are. After the jet line is crossed, however, the thermal hard component disappears.

Radio emission and jets

Fender, Belloni & Gallo (2004) proposed a unified scheme in which the compact flat-spectrum jet emission and the fast relativistic jet component originate from the same outflow, which is accelerated to high Lorentz factors as the source approaches the jet line. Indeed, core radio emission is observed only in the LS (down to quiescence level, see Gallo, Fender & Hynes 2004) and HIMS. The remaining two states, SIMS and HS, do not show radio emission.

Noise and QPO components

As shown above, the properties of the fast time variability are complex, but it is useful to examine their behavior in relation to the states described above. Two states, LS and HIMS, show strong band-limited noise and type-C QPOs; the frequencies of these power-spectrum components follow correlations that suggest there is a one-to-one correspondence between components in the two states (see Belloni, Psaltis & van der Klis 2002). Interestingly, these frequencies vary over a large range in the states where large variations in the inferred inner disk radius are observed. Their energy spectrum is hard (see e.g. Rodriguez et al. 2004; Casella et al. 2004). The two soft states, HS and SIMS, while displaying a number of transient feature such as type-A/B QPOs and other weak components difficult to classify (see Casella et al. 2004,2005; Belloni et al. 2005), never show strong band-limited noise components such as those described above. The QPOs in these states, in particular type-B QPOs, vary over a much smaller range of frequencies compared to the type-C ones. Their spectrum is also hard (Casella et al. 2004). The few instances of high frequency QPOs in BHBs were all observed in the SIMS (see e.g. Morgan, Remillard & Greiner 1997; Homan et al. 2001,2003; Cui et al. 2000; Remillard et al. 1999).

DISCUSSION

Above, we discussed the presence of four states of BHBs, which are identified in terms of the presence/absence of three spectral components, two or more power-spectral components, and a radio-emitting jet with varying Lorentz factor.

Before the 90’s, when only relatively sparse data were available, two BHB states were clearly defined: a low/hard state and a high/soft state. The general picture that can be drawn from the properties discussed above is now the following. In the hard state, the source is jet-dominated, in the sense that the power in the jet is probably larger than that in the accretion (see Fender, Gallo & Jonker 2003). The dominant component in the X-ray range is the thermal hard component, which is possibly associated to the

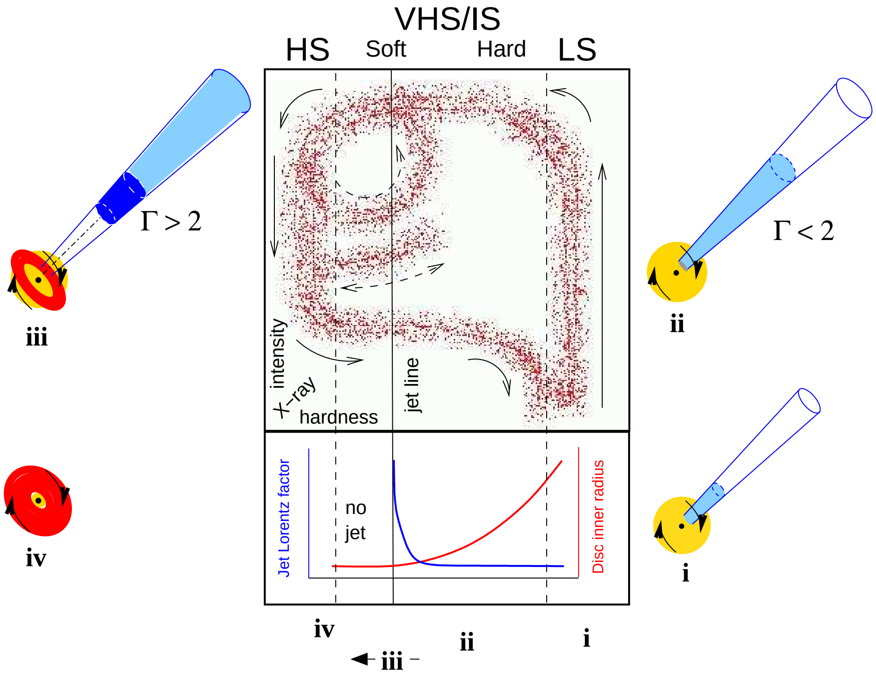

FIGURE 3. Schematic view of the accretion/ejection coupling in BHBs. The top panel shows an idealized HID, the bottom panel shows the Γ factor of the jet and the value of the inner accretion disk radius (see text). The pictures on the side sketch the structure of the three components in the system: jet, disk, and corona. From Fender, Belloni & Gallo (2004).

jet itself. The geometrically thin, optically thick, accretion disk is very soft and has a varying inner radius, so that its contribution to the X-ray emission changes. This state is characterized by strong band-limited noise and type-C QPOs, whose characteristic frequencies show clear correlations between themselves and with spectral parameters (see Wijnands & van der Klis 1999; Psaltis, Belloni & van der Klis 1999; Belloni, Psaltis & van der Klis 2002; Markwardt, Swank & Taam 1999; Vignarca et al. 2003). This state includes the LS and HIMS: the latter is associated to small accretion disk radii, faster jet ejection, steeper energy spectra and higher characteristic frequencies. In the HIMS, the corona component (see below) starts contributing to the X-ray flux (Zdziarski et al. 2001; Rodriguez et al. 2004).

In the soft states (HS and SIMS), the jet is suppressed (jet radio and X-ray components are not observed). The flux is dominated by the accretion disk component, which now has a higher temperature and a small inner radius, possibly coincident with the innermost stable orbit around the black hole, but an additional steep power-law component, with no evidence of a high-energy cutoff up to ∼1 MeV is visible, which we associate here (generically) to a corona. In the power spectra, no strong band-limited noise component is observed, and transient QPOs of type A/B are observed, with frequencies above a few Hz and not much variable.

This picture corresponds to the schematic outburst evolution shown in Fig. 3 (from Fender, Belloni & Gallo 2004) . In addition to the top horizontal branch in Figs. 1 and 3, transitions across the jet line, which separates the two major states described above, can be seen also on short time scales. In XTE J1859+226, very fast transitions are observed between type-B QPOs at 6 Hz and type-C QPOs at 8 Hz, i.e. between the SIMS and the HIMS with high characteristic frequencies (Casella et al. 2004). These transitions have been seen at times corresponding to major radio activity (Casella, this volume). This association resembles that seen in GRS 1915+105 (Klein-Wolt et al. 2002; Fender & Belloni 2004). These short-term transitions should be studied in more detail. Although timing analysis of the fast variability of BHBs can give us direct measurements of important parameters of the accretion flow, up to now we do not have unique models that permit this. Recent results show that a clear association can be made between type-C QPO, strong band-limited noise and the presence of a relativistic jet. In the framework of unifying models, these results could play an important role.

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