Black-Hole Transients: From QPOs to Relativistic Jets

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Abstract

Due to the impressive amount of new data provided by the RXTE satellite in the past decade, our knowledge of the phenomenology of accretion onto black holes has increased considerably. In particular, it has been possible to schematize the outburst evolution of transient systems on the basis of their spectral and timing properties, and link them to the ejection of relativistic jets as observed in the radio. Here, I present this scheme, concentrating on the properties of the quasi-periodic oscillations observed in the light curves and on the link with jet ejection.

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1 Introduction

The RossiXTE mission has changed our view of the high-energy emission of Black Hole Transients (BHT), 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, Fender et al. 2004). 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 et al. 2004). Although a full discussion would necessitate a much longer paper, I will simplify the picture as much as possible, concentrating on the most important issues. In particular, I will stress the connection between fast-timing properties and presence of a jet.
2 Black Hole States

The results of detailed timing and color/spectral analysis of the RossiXTE data of bright BHTs 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, I consider the following states in addition to a quiescent state (see Homan & Belloni 2005; Belloni et al. 2005; see also Casella et al. 2004,2005a for the description of the different QPO types):

- **Low/Hard State (LS):** this state is the one associated to relatively low values of the accretion rate, i.e. lower than in the other bright states, but it can be observed at all luminosities. The energy spectrum is hard and the fast time variability is dominated by a strong (\(\sim 30\%\) 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 et al. 2002). In this state, flat-spectrum radio emission is observed, associated to compact jet ejection (see Gallo et al. 2003; Fender et al. 2004).

- **Hard Intermediate State (HIMS):** 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. 2005a). 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 et al. 2004). Just before the transition to the SIMS (see below), Fender et al. (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. The few instances of high-frequency QPOs in BHT were observed in this state (see e.g. Morgan et al. 1997; Homan et al. 2001,2003; Cui et al. 2000; Remillard et al. 1999).

- **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 classification originates from the analysis of the time evolution in BHTs. 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 the transitions (see Homan & Belloni 2005; Belloni et al. 2005). Figure 1 shows the outburst in a Hardness-Intensity Dia-
Fig. 1. Hardness-Intensity diagram of the 2002/2003 outburst of GX 339-4 as observed by the RXTE PCA. The lines mark the four source states described in the text. The dashed line shows the position of the ‘jet line’. The thick line, intended as a prolongation of the jet line, indicates the transition line that marks the presence/absence of strong band-limited noise. The inset on the lower left shows the general time evolution of the outburst along the ‘q’-shaped pattern. From Belloni et al. (2005).

gram (HID): the x-axis shows the X-ray hardness and the y-axis the detected count rate (from Belloni et al. 2005). The general direction of the time evolution of the outburst is shown by the arrows in the bottom left corner. As described in detail below, the position of the boundaries between different states are absolutely not arbitrary, but are based on the presence of sharp changes in the observed properties.

3 State transitions and jet ejection

The states outlined above are defined in terms of their transitions, unlike other proposed state-classifications (see McClintock & Remillard 2005). However, as I will show, some transitions appear to be more relevant than others.
Fig. 2. Sample PDS from the 2002/2003 outburst of GX 339-4. Left panel: PDS from a SIMS observation (gray points) and average PDS from the HS (black points). Right panel: PDS from a LS (gray points) and a HIMS observation (black points). The difference in the level of variability between the two panels is evident. Data from Belloni et al. (2005)

- **LS to HIMS**: the position of this transition in the HID can be debated, as the color and timing properties change rather smoothly. However, Homan et al (2005) showed that abrupt changes in the infrared/X-ray correlation are observed in correspondence of a particular date, which provides a strong mark for the position of the transition. The IR/X-ray correlation is positive before the transition, then switches to negative after the transition. The timing properties do show evidence of changes (see Belloni et al. 2005), but in a rather smooth way.

- **HIMS to SIMS**: here the transition is very sharp. The power spectra change from band-limited noise plus type-C QPO to red noise plus type-A/B QPO on a time scale that can be as short as a few seconds (see Nespoli et al. 2003, Casella et al. 2004). Color changes are not that marked, and indeed from INTEGRAL data of the 2004/2005 outburst of GX 339-4 there is evidence that during such a transition the hard spectral component changes smoothly (Belloni et al. 2005, in prep.).
• **SIMS to HS:** after the transition line in Fig. 1, all observations do not show any evidence of features in the power spectrum. Although some SIMS observations also appear very quiet, it is remarkable that below a certain source rate, no more signal is detected. Averaging all observations, a weak power law is observable in the power spectrum (see Fig. 2).

• **HS to HIMS:** the line in Fig. 1 clearly marks the appearance of strong band-limited noise (plus type-C QPOs). The three observations that moved back to the left of this line do not have this noise, indicating that there is indeed a color boundary.

• **HIMS to LS:** as in the case of the reverse transition, the color and timing properties do not show strong discontinuities in their evolution. The transition line is placed at the same color as the reverse transition.

In the model of Fender et al. (2004), the HIMS–SIMS transition corresponds to the ‘jet line’, which marks the time of the sudden quenching of a rapidly accelerating radio jet (see also Corbel et al. 2004). Notice that in some sources this transition can be repeated: in GRS 1915+105, it takes place on all time scales, and radio oscillations are observed to correlate with it (see Eikenberry et al. 1998, Klein-Wolt et al. 2002). Also in XTE J1859+226, rapid transitions are observed: it is interesting to notice that the appearance of type-B QPOs, tracers of the SIMS, appear roughly in correspondence of radio flares (see Casella et al. 2005b).

4 **Two states only?**

The jet line does not extend to the low part of the diagram, but a discontinuity line can be traced vertically (see Fig. 1). To the right of this line, marked ‘radio-loud’, where a radio emitting jet component exists, there is strong band-limited noise in the power spectrum, often accompanied by type-C QPOs whose frequencies correlate with spectral parameters (see Vignarca et al. 2003). To the left of this line, marked ‘radio-quiet’, no strong core radio emission is observed (see Fender et al. 1999) and the power spectrum does *not* show strong noise, with the occasional presence of a type-A/B QPOs, whose frequencies vary only over a small range (see Casella et al. 2005a). Typical power spectra (from GX 339-4) can be seen in Fig. 2.

The clear separation in timing and radio properties of the hard (LS and HIMS) and soft (SIMS and HS) states can be seen in Fig. 3, where the time evolution of the integrated fractional rms of GX 339-4 during. This indicates that the four states presented above, in terms of physical conditions, might be reduced to only two: a hard state characterized by radio-loudness, strong noise components and variable-frequency type-C QPOs, and a soft one, radio-quiet, with weak power-law noise and transient type-A/B QPOs.
It is important to note that major tracers of these states are low-frequency QPOs and associated noise components. Type-C QPOs and band-limited noise components provide characteristic frequencies that trace the evolution of the accretion during the early and final part of the outburst; in the hard states, the strong correlations between hard X-ray emission and radio flux led to models for the jet production and X-ray emission which need to take these timing tracers into account (see e.g. Meier 2005). Type-A/B QPOs are much less studied and their origin is unclear. However, the transient presence of type-B QPOs could be important for the study of the physical conditions of the accretion flow as the source crosses the jet line. The small range of long-term variability of their centroid frequency, its fast short-term variability (see Nespoli et al. 2003; Belloni et al. 2005) and the absence of band-limited noise components are key ingredients for their understanding (see Casella et al. 2005a).
The general picture that can be drawn from the properties discussed above is the following. In the hard state, the source is probably jet-dominated, in the sense that the power in the jet is larger than that in the accretion (see Fender et al. 2003). The dominant component in the X-ray range is a thermal hard component, which is possibly associated to the jet itself (see e.g. Markoff et al. 2003 and Nowak et al. 2005). 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; Belloni et al. 2002; Markwardt et al. 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 (radio and X-ray jet components are not observed). The flux is dominated by the optically thick 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 power-law component, with no evidence of a high-energy cutoff up to \(\sim 1\) MeV is visible, which I 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 on time scales longer than a few seconds (Casella et al. 2005a).

The above picture involves four observationally separated states, two physical states and three emission components: the optically thick disk, the thermal hard component and the corona component. Their contribution to the fast time variability is markedly different: the disk component does not contribute to it, the thermal hard component is associated to the band-limited noise and type-C QPOs, and the corona component is associated to the type-A/B QPOs and the weak power-law variability observed in the soft states. A key ingredient is the HIMS–SIMS transition: the transition itself is marked by the timing properties, but the spectral evolution through it is far from being clear. Recent INTEGRAL data suggest that the transition between the thermal component being dominant (as in the LS) and the corona component being visible at high energies (in the HS) is smooth across the jet line (Belloni et al. 2005, in prep.).

Although timing analysis of the fast variability of BHTs 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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