Noisy Jets and Emission Components in Galactic X-Ray Binaries

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Abstract. Our knowledge of the phenomenology of accretion onto black holes has increased considerably thanks to ten years of observations with the RXTE satellite. However, only recently it has been possible to derive a scheme for the outburst evolution of transient systems on the basis of their spectral and timing properties, reaching a comprehensive definition of source states. These states are in turn linked to the ejection of relativistic jets as observed in the radio band. Here I concentrate on some specific aspects of this classification, concentrating on the properties of the aperiodic variability and on their link with jet ejection.

Keywords: accretion: accretion disks – black hole physics – stars: oscillations – X-rays: binaries

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INTRODUCTION

The picture of high-energy emission from Black-Hole Transients (BHT) that is emerging after more than a decade of observations with the RossiXTE satellite is complex and difficult to interpret, yet it is a considerable step forward in our knowledge. Only recently, it has been possible to find a sufficiently stable pattern in the spectral and timing properties to obtain a coherent picture. The classification of states and state-transition derived from a few objects is applicable to most systems, indicating that the common properties are more than what previously known (see [1, 2, 3] but also [4, 5]). At the same time, a clear connection between X-ray and radio properties has been found (see [6, 7]).

In this paper, I examine a few aspects of this picture, highlighting the connection between noise components, spectral properties at energies >20 keV, source states and radio/jet properties.

SOURCE STATES

The color and timing analysis of GX 339-4, extended to other bright transients, has led to a definition of four source states defined in terms of transitions between them. For a complete definition of the four bright source states see e.g. [1, 2, 8], while [9] adopt a different state classification based on the parameters obtained from spectral and variability components. To follow the evolution of an outburst through different states, three direct observables proved to be fundamental. The first is the X-ray intensity of the source, expressed in count rate; the more physical source-integrated flux can be used, but its derivation is model dependent. The second is a measure of the hardness of the
spectrum, namely the ratio between count rates in a hard and a soft band. This has the advantage of yielding a model-independent measure of the hardness of the source spectrum: once associated to a chosen spectral decomposition, this quantity can be turned into a physical parameter. Finally, the third is a measure of the variability in the X-ray band, expressed as fractional rms integrated in a reasonably wide frequency range. Of course, energy spectra and power spectra, together with their decomposition in different models, are important for the physical understanding, but they are not necessary to describe the outburst and will be discussed later. With these three quantities, two diagrams are constructed: the Hardness-Intensity diagram (HID) and the hardness-rms diagram.

The HID of the 2002/2003 outburst of GX 339-4 as observed by RXTE/PCA is shown in Fig. 1. The regions corresponding to the four states discussed below are marked. Fig. 2 shows the corresponding rms-hardness diagram: on the X-axis is the same hardness than in Fig. 1, while on the Y-axis is the integrated fractional rms variability in the 0.1–64 Hz band.

In the following, I concentrate on some aspects of the states that can be identified from these diagrams:

• Two states, the Low/Hard (LS) and Hard-Intermediate (HIMS), found at the right of the thick vertical line in Fig. 1 have a number of aspects in common. A strong hard component is visible in their energy spectrum, usually attributed to (thermal) Comptonization. In the LS, this can be approximated with a power law with spectral index 1.6-1.8 and a high-energy cutoff around 100 keV. Since the source points are distributed along an almost vertical line, it is clear that the spectral changes in this state are small (at least below ∼20 keV), while there is a flux increase by a factor of ∼100. In the HIMS, the slope is higher (2.0-2.4) and the high-energy cutoff moves to lower energies (see [10]). In addition, a soft thermal disk component appears. The strong hardness variation along the horizontal line are a combination of the steepening of the hard component and the appearance of the thermal disk. In both states, the power spectrum is dominated by a band-limited component, with the presence of a type-C QPO in the HIMS (see [11]). The fractional rms decreases smoothly from 50 % at the beginning of the LS to 10% at the end of the HIMS (see Fig. 2). These states correspond to detectable radio emission from the core source, associated with compact jet ejection. Just before the transition to the Soft-Intermediate state, it was suggested that the jet velocity increases rapidly, giving origin to the fast relativistic jets [7].

• The other two states, the High/Soft (HS) and Soft-Intermediate (SIMS), are markedly different, In both, the energy spectrum is dominated by a thermal disk component, with only a weak steep hard component visible without a high-energy cutoff (see [12]). Again, the small hardness variations in this state (notice that the hardness scale in Fig. 1 is logarithmic) indicates that there are no strong spectral changes in the HS. The power spectrum does not show a strong band-limited noise, but rather a weaker power-law component. In the SIMS, strong type-A/B QPOs are observed, while in the HS occasionally weak QPOs are observed, which cannot be easily identified with the ABC types (see [11, 8]). As one can see from Fig. 2 the integrated fractional rms is below 10% and goes down as low as 1% at the
FIGURE 1. Hardness-Intensity diagram of the 2002-2003 outburst of GX 339-4 as observed by the RXTE/PCA, adapted from [2]. The lines mark the four source states described in the text. The different symbols are described in [8]. The dashed line shows the position of the ‘jet line’. The thick line indicates the transition line that marks the presence/absence of strong band-limited noise in the power spectra. The inset on the lower left shows the general time evolution of the outburst along the q-shaped pattern.

soft end. Moreover, the HS points (triangles and dots) follow a continuation of the rms-hardness correlation of the LS/HIMS, while the SIMS points deviate from it, being at lower rms values (boxed area in Fig. 2). Also notice that when the source returned to the HIMS at the end of the outburst (black circles), only one point can be attributed to a SIMS, while the others followed the rms-hardness correlation all the way to the right. These states, to the left of the ‘jet line’, correspond to non-detectable emission from the central source (see [13, 7]). However, the multi-wavelength analysis of an outburst of three transients showed that the core radio emission turns on only when the source reaches the LS ([14, 15, 16]).

Obviously, the four states can be grouped into two ‘classes’: the hard and radio-loud ones (LS and HIMS, although radio emission is observed in the HIMS only at high luminosities, see [15, 16]) and the soft and radio-quiet ones (HS and SIMS). The evolution from hard to soft causes a crossing of the jet line: the velocity of the outflow
increases rapidly when approaching the line, creating fast propagating shocks in the jet [7]. The evolution from soft to hard simply leads to the (slow) formation of a new outflow, only mildly relativistic, and cannot give rise to fast relativistic ejections.

The focus here is obviously on the transitions between states, which mark very clearly the division between them. The transition between LS and the HIMS is clearly marked by changes in the infrared/X-ray correlation and can be placed very precisely in the evolution of the outburst [14, 8]. The transition between HIMS and SIMS is marked by abrupt changes in the timing properties, with the appearing of type-A/B QPOs and the dropping of the noise level (see Fig. 3). From SIMS to HS, a recovery of the noise level and disappearing of type-A/B QPOs is observed.
FIGURE 3. Power density spectra of two RXTE observations of GX 339-4 from 2004 August 15. The two observations were separated by about 8.5 hours. Left panel: HIMS before the transition; right panel: SIMS after the transition. For a full analysis of these data, see [10].

TIME VARIABILITY AS A TRACER

No light curve is shown in the figures here. It is not necessary to examine the time evolution, as the evolution of the system can be synthesized with only the two plots in Figs. 1 and 2. In particular, Fig. 2 is particularly important, as it shows at the same time the color (spectral) and rms (timing) evolution. The presence/absence of specific noise components and/or QPOs, with related problems of significance of detection, is not necessary in order to characterize the source states in these diagrams.

In Fig. 1, the source follows a very different path moving from hard to soft at the beginning of the outburst than it does the opposite transition at the end of the outburst. This hysteresis cycle has been discussed in the past (see [19, 20]). However, notice that there is no trace of hysteresis in Fig. 2: here the source traces the same path throughout the early and late phases of the outburst. Since the bright and weak transitions take place at different values of mass accretion rate, this indicates that the global timing properties do not depend on this parameter.

It is evident from Fig. 2 that the timing properties are tracers of the evolution of the accretion flow and the jet properties. The crossing of the jet line can be identified by the drop in integrated rms and by the appearance of type-A/B QPOs, easily identifiable in the power spectra. Notice that the recent analysis of the radio/X-ray properties of a number of systems suggest that the association between crossing the jet line and entering the SIMS is not precise: the ejection time of the jet can lead or lag the start of SIMS by a few days ([21]).

In addition to the integrated variability properties, specific features in the power spectra are important players in the game. 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. [17]). 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 [18, 8]) and the absence of band-limited noise components are key ingredients for their understanding (see [11]).

CONCLUSIONS: NOISY ACCRETION AND EJECTION

The general picture that is emerging is becoming more and more clear and it can be applied to a large sample of systems [3]. In particular, the details of the changes in the X-ray emission when crossing the jet line appear crucial for the modeling of the accretion/ejection connection. Although the timing properties change on a very short time scale, at low (<20 keV) energies spectral changes are minimal, as can be seen by the small difference in X-ray hardness (see e.g. [18]). Recently, evidence for a possible fast change in the spectral properties at energies >20 keV was gathered [10], although more high-energy data on this elusive transition should be obtained.

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.

REFERENCES

1. J. Homan, T. Belloni: AP&SS 300, 107 (2005)
2. T. Belloni: Adv. Sp. Res. in press (astro-ph/0507556) (2006)
3. J. Homan, T. Belloni: in preparation (2006)
4. J.A. Tomsick, S. Corbel, A. Goldwurm, P. Kaaret: ApJ 630, 413 (2005)
5. J.A. Tomsick: Adv. Sp. Res. in press (astro-ph/0509110) (2006)
6. R.P. Fender: Jets from X-ray binaries. In: Compact Stellar X-ray Binaries, ed by W.H.G. Lewin, M. van der Klis (Cambridge Univ. Press, Cambridge 2006).
7. R.P. Fender, T. Belloni, E. Gallo: MNRAS 355, 1105 (2004)
8. T. Belloni, J. Homan, P. Casella, et al.: A&A 440, 207 (2005)
9. R.A. Remillard, McClintock, J.E.: ARA&A 44, 49 (2006)
10. T. Belloni, I. Parolin, M. Del Santo et al.: MNRAS 367, 1113 (2006)
11. P. Casella, T. Belloni, L. Stella: ApJ 629, 403 (2005)
12. J.E. Grove, W.N. Johnson, R.A. Kroeger, et al.: ApJ 500, 899 (1998)
13. S. Corbel, R.P. Fender, J.A. Tomsick, et al.: ApJ 617, 1272 (2004)
14. J. Homan, M. Buxton, S. Markoff, et al.: ApJ 624, 295 (2005)
15. E. Kalemci, J.A. Tomsick, M.M. Buxton, et al.: ApJ 622, 508 (2005)
16. E. Kalemci, J.A. Tomsick, R.E. Rothschild, et al.: ApJ 639, 340 (2006)
17. D.L. Meier: Adv. Sp. Res. 300, 55 (2005)
18. E. Nespoli, T. Belloni, J. Homan, et al.: A&A 412, 235 (2003)
19. S. Miyamoto, S. Kitamoto, K. Hayashida, et al.: ApJ, 442, L13 (1995)
20. T.J. Maccarone, P.S. Coppi: MNRAS 338, 189 (2003)
21. Fender, R.P., et al., in preparation (2006)