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Spectral state transitions in GX 339–4

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We report on *INTEGRAL* observations of the bright black-hole transient GX 339−4 performed during the 2004 outburst. Our data cover three different spectral states, namely Hard/Intermediate State (HIMS), Soft/Intermediate State (SIMS), High/Soft State (HSS). Fits of joint IBIS, SPI and JEM-X data are well represented by hybrid thermal/non-thermal Comptonization (EQPAIR) and allow us to track the evolution of each spectral component during the transitions. Furthermore, spectra of GX 339−4 in the HIM state show a high energy excess with respect to pure thermal Comptonization models. We present a summary of these results, extensively discussed in a recently published work, as well as, a comparison of the 2004 transition with a "secondary" transition HIMS-to-SIMS observed during the 2007 outburst with *RXTE* and *INTEGRAL*, simultaneously.

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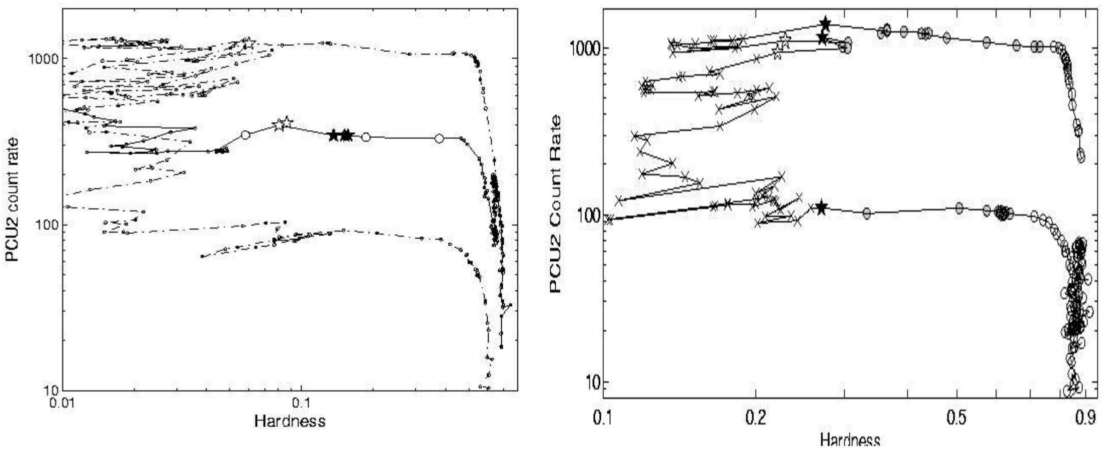

Figure 1: GX 339−4 Hardness Intensity Diagrams of the 2002/2003, 2004 (*left*) and 2007 (*right*) outbursts.

1. The 2004 and 2007 outbursts of GX 339−4

In February 2004 an outburst from the transient black hole candidate (BHC) GX 339−4 was observed [4, 1]. It was fully followed by *RXTE* and observed two times by the *INTEGRAL* satellite: during the first part of the hard X-ray activity (February 19–March 20) and during the decay of the hard X-ray flux, i. e. August 9–September 11. On August 15th, a fast spectral state transition HIMS-to-SIMS was reported by Belloni et al. (2006). Although spectral parameters at lower energies did not change abruptly through the transition, the high-energy cut-off ($\sim$70 keV) disappeared after the transition within 10 hours. Power spectra showed strong band-limited noise and type-C QPO before the transition and weaker noise and type-B QPO after the transition. The 2004 outburst of GX 339−4 reached a significantly lower peak flux (more than a factor of 3) than the one observed in 2002/2003 [2].

In 2006 December a new strong outburst (at same peak-flux level of the 2002/2003 one) started. Miller et al. (2007) triggered a public *INTEGRAL* ToO campaign on GX 339−4 from January 30th. We activated our *RXTE* campaign with the aim to follow the source through a HIMS-to-SIMS transition. We did not observe the main transition (as in 2004), even though we managed to capture a secondary transition occurred on March 4–6.

We present in this paper the spectral evolution of GX 339−4 using *INTEGRAL* data collected over a long period of time, covering almost the whole span of the 2004 LHS-HSS transition [5]. Finally, we summarize results of the timing and spectral analysis of *RXTE*/PCA/HEXTE and *INTEGRAL*/IBIS data from 2007 March 4–6 [6] and compare properties of the two transitions.

2. The hardness-intensity diagrams

Hardness-Intensity diagrams from the three outbursts of GX 339−4 occurred in 2002/2003 (Fig. 1 *left* panel, dot-dashed line), 2004 (Fig. 1 *left* panel, continuous line) and 2007 (Fig. 1 *right* panel) are shown. Symbols refer to the QPO-types (see Belloni et al. 2006; Del Santo et al. 2008b). During a typical outburst the source starts in a faint Low/Hard State (LHS), moves upward

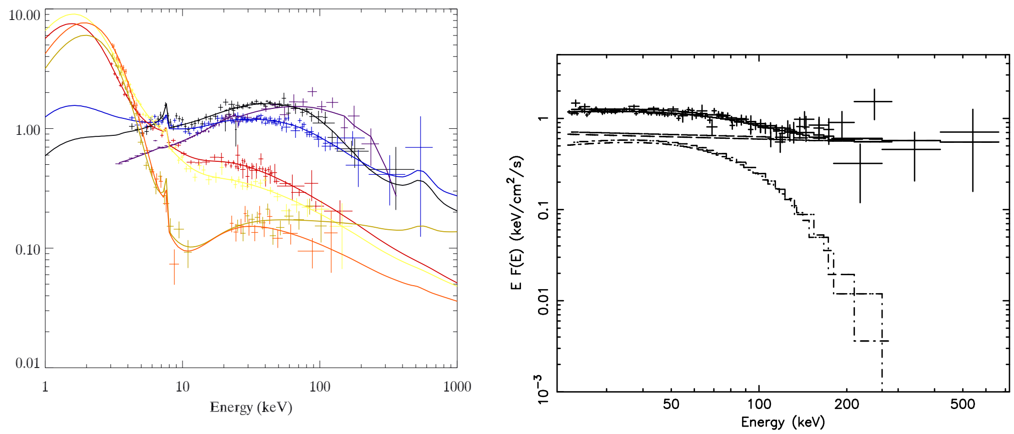

Figure 2: *Left*: Joint JEM-X, IBIS and SPI unfolded energy spectra of GX 339−4 averaged during different spectral states in 2004: HIMS for spectra 1 (black), 2 (blue), 3 (red); SIMS for 4 (yellow); HSS for spectra 5 (green) and 7 (orange). In order to give a comparison with a pure Low/Hard state spectrum, we show a spectrum (violet) reported in Joinet et al. (2007). *Right*: IBIS and SPI energy spectra and residuals of rev 223 fitted with a Comptonization model (COMPPS) plus power-law.

along the LHS branch, then move leftward towards the High/Soft State (HSS) along the Very High State (VHS) branch. When luminosity decreases the source moves down along the HSS before transiting right back to the LHS along the lower horizontal branch, and then back to quiescence in the LHS [8]. A puzzling property of this evolution is that the spectral changes in GX 339−4 lag the variations of the luminosity: hard-to-soft state transitions during the rising phase occur at higher luminosities than the soft-to-hard ones during the declining phase.

In spite of the large range of luminosities at which outbursts occur, we note for the three GX 339−4 HIDs a similar *q*-shaped track pattern as described in Homan & Belloni (2005).

3. Spectral analysis results

We divided in seven groups the *INTEGRAL* observations of GX 339−4 performed between 2004 August 9th and September 11. Spectral parameters obtained by fitting joint JEM-X, IBIS and SPI averaged spectra (Fig. 2, *left*) with a thermal/non-thermal hybrid Comptonization model (EQPAIR) plus DISKLINE are shown in Tab. 1 (see Del Santo et al. 2008a for the parameters description and discussion).

Here, we outline that we found a non-negligible values of l_{nth}/l_h (compactness ratio between the electron acceleration and total power supplied to the plasma) in spectra 1, 2, 3 (see Tab. 1) indicating that a non-thermal emission is also requested by the data. In order to investigate further the possible presence of a non-thermal component during the HIM state, IBIS and SPI spectra of the three HIMS periods have been fitted with COMPPS. Using this thermal Comptonization model, some residuals are present at high energy, especially in the spectrum 2 (see Del Santo et al. 2008a). To mimic the presence of a non-thermal component, we added a power-law to the pure thermal Comptonization model (Fig. 2, *right*). This resulted in an improvement of the χ^2 that is highly significant for orbit 223 (see Del Santo et al 2008a).

4. Discussion

In 2004 we have observed that the GX 339−4 spectral transition was driven by changes in the soft cooling photon flux in the corona associated with an increase of disc temperatures, resulting in a dramatic increase of disc luminosity. The measured disc temperature versus luminosity relation suggests that the internal disc radius decreases. In contrasts, the heating rate of the electrons in the corona appears to remain nearly constant. Although other models such as dynamic accretion disc corona models cannot be ruled out, these results are consistent with the so-called truncated disc model [7]. Moreover, in all GX 339−4 spectra, including those in HIMS, we found a significant contribution from a non-thermal component. This component appears as a high energy excess above the pure thermal Comptonization spectrum. We associated this component with the presence of a non-thermal tail in the distribution of the Comptonizing electrons.

4.1 Comparison with 2007 transition

The work on the 2007 transition will be published in Del Santo et al. (2008b). Here we shortly report on the main result and difference between the 2004 and 2007 outbursts.

In 2007 we observed a "mini-transition" HIMS-to-SIMS in GX 339−4 which occurred on a secondary horizontal branch of the q-track. An important change in the power-law flux component was observed during this transition, clearly marked by changes in the properties of fast a-periodic timing from C-type to A-type QPO. This suggested that power-law flux and timing are tightly correlated during the fast transitions. On the other hand, changes in the high energy cut-off and photon index appeared between the two HIMS observations rather than between the HIMS and the SIMS. A slight delay between variations of the spectral parameters and the ones of the hard-X flux and timing properties has been observed.

In conclusion:

- the 2004 outburst peaked at a considerably lower luminosity than that of 2007;
- after the transition, in 2004 a type-B QPO was observed, while in 2007 a type-A QPO was observed;
- in 2004, the major HIMS to SIMS transition was observed on the primary horizontal branch, while in 2007 it was on a secondary branch;
- in 2004 the high energy cut-off disappeared after the transition, while in 2007 we observed that it decreased.

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Table 1: Best-fit parameters of the joint IBIS/ISGRI, JEM-X and SPI spectra (only rev 222, 223 and 224.1 for the spectrometer). Fits have been performed simultaneously with EQPAIR combined with DISKLINE. See text for the parameters description.

Period	Rev	l_h/l_s	l_{nth}/l_h	τ_{es}	kT_{bb} [eV]	$\Omega/2\pi$	G_{inj}	τ_{tot}	kT_e [keV]	χ^2_ν(dof)	Flux $\times 10^{-9}$ [erg cm^{-2} s^{-1}]		
											Bol	*bb*	*Compt*
1	222	$4.36^{+1.02}_{-0.39}$	$0.75^{+0.25}_{-0.14}$	$2.58^{+0.24}_{-0.93}$	(300)	$0.23^{+0.26}_{-0.13}$	$2.75^{+0.46}_{-0.64}$	2.72	23.2	0.99(243)	11.3	1.0	9.4
2	223	$2.10^{+0.40}_{-0.39}$	$1.0^{+0}_{-0.17}$	$1.96^{+0.31}_{-0.49}$	(300)	0.6 ± 0.3	$2.62^{+0.27}_{-0.37}$	2.05	19.2	1.17(219)	12.4	2.1	8.9
3	224.1	$0.20^{+0.05}_{-0.07}$	$0.71^{+0.18}_{-0.09}$	$0.18^{+0.12}_{-0.03}$	380^{+54}_{-57}	$1.0^{+0.10}_{-0.35}$	$2.91^{+0.14}_{-0.22}$	0.20	45.0	1.14(215)	21.0	15.4	5.6
4	224.2	$0.17^{+0.03}_{-0.02}$	$0.56^{+0.11}_{-0.10}$	$0.36^{+0.34}_{-0.12}$	388^{+76}_{-83}	(1)	$2.86^{+0.37}_{-0.18}$	0.36	29.4	1.06(173)	24.3	17.8	6.5
5	226	$0.15^{+0.13}_{-0.05}$	$0.94^{+0.06}_{-0.10}$	< 0.1	495^{+27}_{-43}	(1)	1.9 ± 0.3	0.1	21.7	1.15(121)	13.8	10.9	2.9
7	232-233	$0.07^{+0.04}_{-0.01}$	$1.0^{+0}_{-0.2}$	< 0.7	478^{+66}_{-83}	(1)	$2.8 \pm +0.5$	0.7	5.5	1.0(98)	18.4	13.8	4.2

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