Spectral properties of transitions between soft and hard state in GX 339-4

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We investigate the spectral properties during state transitions in the 2010 outburst of GX 339-4, which was densely covered by the Rossi X-ray timing explorer (RXTE). We select all observations, including those that show type-B quasi periodic oscillations (QPOs), within a certain hardness ratio range during the soft intermediate state (SIMS). We find that the power-law component of the energy spectrum is significantly flatter during the SIMS of the soft-to-hard transition than it is during the hard-to-soft transition. This demonstrates that during the SIMS of the soft-to-hard transition not only the luminosity and centroid frequencies of type-B QPOs are lower, but that also the photon index is lower, compared to the hard-to-soft transition. Hence, type-B QPOs are not necessarily associated to a particular spectral shape. However, in each branch only certain combinations of centroid frequency and photon index are realised.

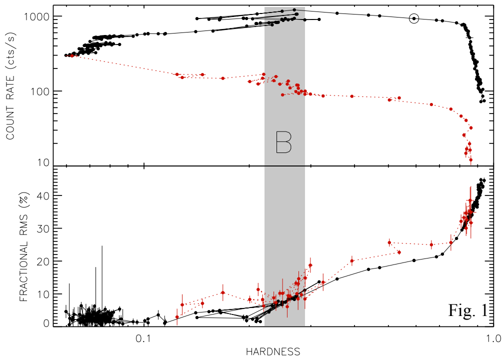


Fig. 1

GX 339-4, a black hole X-ray transient (BHT), is a low mass X-ray binary, harbouring a > 6 $M_\odot$ black hole accreting from a subgiant star in a 1.7 d orbital period (Hynes et al. 2003; Muñoz-Darias et al. 2008).

The 2010 outburst of GX 339-4 was densely covered by RXTE, providing the best coverage of the state transitions between the LHS and the HSS. The hardness intensity diagram (HID) as well as the hardness-rms diagram (HRD) of the whole outburst are shown in Fig. 1. Consecutive observations are joined by a solid line until the softest observation is reached; after that by a (red) dashed line.

The sample: In the transition from the LHS to the HSS, in the following called the upper branch, we selected all observations that show a type-B QPO. These observations have a hardness ratio ranging from 0.2208 to 0.2883 (grey shaded area in Fig. 1). This hardness ratio range also includes observations without a type-B QPO. The same hardness ratio range was used to select observations from the lower branch (the back transition from the HSS to the LHS at lower luminosities). All observations showing type-B QPOs on either branch are within the hardness ratio range used. On the upper branch the centroid frequency of the type-B QPOs is ~5 Hz, while on the lower branch it reduces to ~2 Hz (see Motta et al. 2011, in prep.). The fractional rms of observations showing type-B QPOs lies in the expected 5 – 10 % range (see Muñoz-Darias et al. 2011). Furthermore, observations with a type-B QPO have a lower fractional rms during back transition than in the hard-to-soft transition. For most of the remaining parts of the outburst the fractional rms during back transition is higher than it was in the hard-to-soft transition (observations belonging to the back transition are marked in red in Fig. 1). We also analysed HIMS observations (0.2883 < HR ≤ 0.8) to cover the whole transition.

Spectral fitting: Since we are only interested in the behaviour of the hard spectral component we decided to neglect the contribution of the soft (disc) component and to focus our spectral analysis on the high energy range. We fitted PCA (10 – 40 keV) data using a power law model. For the first few observations of the HIMS an additional high energy cut off was needed to obtain good fits. We also tried a different model, consisting of a power law multiplied by a reflection component. We found that the relative reflection component is only needed for the first few HIMS observations. In the remaining observations the relative reflection component found is always consistent with zero within errors.

Lower luminosity, lower centroid frequencies of type-B QPOs and even lower photon index in the soft-to-hard transition:

- The soft-to-hard transition takes place at a much lower photon index (see Figs. 2, 3) than the hard-to-soft transition.
- Hardness ratio can be used as a good tracker of the spectral shape for observations obtained at more or less the same flux. However, it is necessary to “re-calibrate” its meaning according to the flux level, if observations at different fluxes are compared.
- The connection between source flux and photon index (Fig. 4) is as expected according to the HID.
- The hardness ratio range of the sample is represented as a vertical strip in the HID. The jet line does not follow a vertical line in the HID, but shows a more complex behaviour (Fender et al. 2009; Kalemci et al. 2006; Russell & Lewis 2011). The lines of constant photon index run from the upper right to the lower left in the HID during state transition.
- The photon indices found in the SIMS of the lower branch correspond to values obtained at the onset of the HIMS in the upper branch (see encircled dot in Fig. 1). This finding is in agreement with the lagging of timing properties compared to spectral properties in the soft-to-hard transition, as reported in Kalemci et al. (2004).
- It is known that the disappearance of the radio jet in the upper branch and the re-appearance of the jet in the lower branch takes place at different hardness ratios. Our finding of a lower photon index during the SIMS of the lower branch implies that the jet appears at a much lower photon index in the soft-to-hard transition than it disappeared at in the upper branch. Hence, there is either no relation between photon index and radio emission or this relation has to be extremely complicated.
- Type-B QPOs are not necessarily associated to a particular spectral shape. In the upper branch type-B QPOs appear at a centroid frequency of ~5 Hz and in observations where the photon index is between 2.3 and 2.6. In the lower branch the centroid frequency of type-B QPOs reduces to ~2 Hz and they are mainly observed in observations which spectra have a photon index of ~1.9 (see Fig. 3). However, we observe type-B QPOs neither in observations of the upper branch that have a photon index of ~1.9 nor in observations of the lower branch which have a photon index of ~2.4. Therefore, the physical conditions that lead to the QPO do not depend in an obvious way on the power law parameters. Figure 3 clearly shows that within each branch the photon index is not enough to distinguish between observations with and without type-B QPOs in the sample selected. The difference is just in the timing.
- Type-B QPOs can appear only in a very narrow range of properties of a BHT which are realised during state transitions. These properties occur in a rather narrow window in the HID and they are characterised by selected combinations of peak frequencies of type-B QPOs and photon index in the upper and lower branch, respectively. Whether the appearance of type-B QPOs is related to changes in the disc, corona, accretion process, or a combination of several processes is still unclear and should be the topic of further investigations.

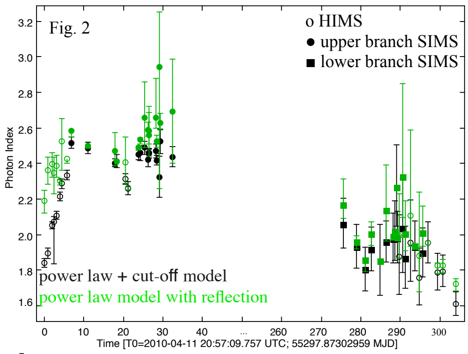
Fig. 2


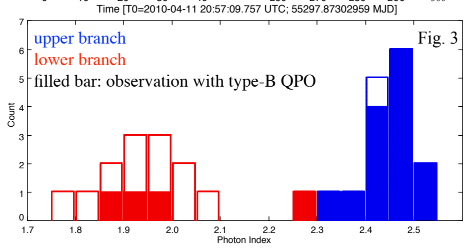
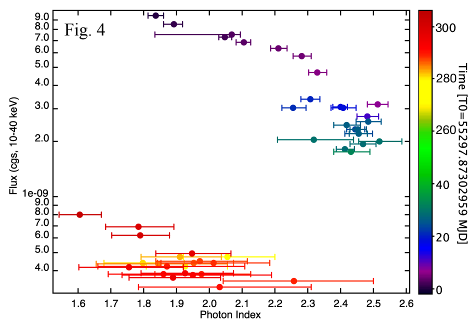
Fig. 3


Fig. 4


Technical issues:
PCA/Proportional Counter Unit 2 (PCU2) data
Intensity: STD2 channels 0 – 31 (2 – 15 keV)
Hardness ratio:
soft band: STD2 channels 7 – 13 (2.87 – 5.71 keV)
hard band: STD2 channels 14 – 23 (5.71 – 9.51 keV)
rms frequency band: 0.1 – 64 Hz
spectra extracted within HEASOFT V. 6.9 and fitted with ISIS V.1.6.1 (Houck & Denicola 2000)

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