SF2A 2016
C. Reylé, J. Richard, L. Cambrésy, M. Deleuil, E. Pécontal, L. Tresse and I. Vaughlin (eds)

ENERGY DEPENDENT VARIABILITY AND OUTBURST EVOLUTION IN BLACK HOLE X-RAY BINARIES

H. Stiele[1] and A. K. H. Kong[1]

Abstract. Almost all low mass black hole X-ray binaries are transient sources. Most of these sources show a certain pattern during outburst: the evolution from low hard state through intermediate state(s) into high soft state and the returning to the hard state at lower luminosity. However, there are outbursts that remain in the hard state (so called "failed" outbursts).

Using the technique of covariance spectra we can investigate the variability of individual spectral components on different time scales. Comprehensive studies of covariance spectra for a sample of black hole X-ray binaries observed in the rising low hard state of "normal" outbursts revealed an increase of the covariance ratios towards lower energies that has been interpreted as the sign of additional disc variability on long time scales.

There are now two sources (H 1743-322 and GS 1354–64) that do not show an increase towards lower energies in their covariance ratio. Both sources have been observed during "failed" outbursts and showed photon indices much harder than what is usually observed in black hole X-ray binaries.

Keywords: X-rays: binaries, binaries: close, black hole physics

1 Introduction

In low-mass black hole X-ray binaries (BHBs), a stellar mass black hole accretes matter from its low-mass, early type companion star through Roche-lobe overflow. Most of the time, these systems are too faint to be studied with current X-ray instruments. Through the monitoring of BHBs during outbursts with the RXTE satellite for about 15 years a detailed phenomenological picture of the spectral and timing properties of these sources has emerged (Belloni 2010; McClintock & Remillard 2006). We learned that BHBs typically begin and end their outbursts in the low hard state (LHS), and that most sources show transitions to a high soft state (HSS). In the LHS, the energy spectrum is dominated by a hard component, which fitting with simple models extends up to a cut-off energy of $\sim 50 - 100\,\mathrm{keV}$. In addition, a much softer component associated to a thermal accretion disc is sometimes observed when the interstellar absorption is not too high. Strong ($30-40\%$) band-limited noise as well as low frequency quasi-periodic oscillations (LF-QPOs) is observed in the Power Density Spectrum (PDS). In the HSS, the energy spectrum is dominated by a thermal component, usually modeled with a disc-blackbody with a temperature of $1-2\,\mathrm{keV}$. A weak power-law component is present, with a steeper and strongly variable photon index. No apparent high-energy cut-off is observed in high signal-to-noise spectra. The PDS shows weak (few %) power-law noise.

This picture has been challenged in recent years. Investigations of power density spectra at softer energies showed that in the hard intermediate state two distinct power spectral shapes coexist simultaneously in the soft and hard energy band (Yu & Zhang 2013; Stiele & Yu 2014).

There are about ten X-ray binaries (including neutron stars and black holes; Capitanio et al. 2009, and references therein) that have only been observed during outbursts where they did not make the transition to the soft state. This type of outburst has been dubbed "failed" outburst. In the case of H 1743-322 both type of outbursts have been observed (Capitanio et al. 2009; Stiele & Yu 2016). Capitanio et al. (2009) supposed that "failed" outbursts are connected to a premature decrease of the mass accretion rate. At the moment, the physical reason why some outbursts make it to the soft state, while other remain in the hard state, is elusive.

---

[1] National Tsing Hua University, Department of Physics and Institute of Astronomy, No. 101 Sect. 2 Kuang-Fu Road, 30013, Hsinchu, Taiwan

2 Observations and data analysis

We used *XMM-Newton* observations of the 2004 and 2009 outbursts of GX 339–4 (Wilkinson & Uttley 2009; Stiele & Yu 2015), of Swift J1753.5–0127 taken in 2006 and 2012 (Wilkinson & Uttley 2009; Stiele & Yu 2015), of the "failed" outbursts in 2008 and 2014 of H 1743–322 (Motta et al. 2010; Stiele & Yu 2016), and of GS 1354–64 during its outburst in 2015 (Stiele & Kong 2016). All observations were taken during the LHS. We filtered and extracted the pn event files, using standard SAS tools, paying particular attention to extract the list of photons not randomized in time. For our study we selected the longest, continuous exposure available in each observation. We used the SAS task `epatplot` to investigate whether the observations are affected by pile-up, and in the case of pile-up excluded the column(s) with the highest count rate until the selection results in an observed pattern distribution that follows the theoretical prediction quite nicely. We selected single and double events (PATTERN<=4) for our study. More details on individual observations can be found in Stiele & Yu (2015, 2016) and Stiele & Kong (2016).

We produced PDS in several energy bands. We subtracted the contribution due to Poissonian noise (Zhang et al. 1995), normalised the PDS according to Leahy et al. (1983) and converted to square fractional rms (Belloni & Hasinger 1990). The PDS were fitted with models composed of zero-centered Lorentzians for BLN components, and Lorentzians for QPOs following Belloni et al. (2002).

We also extracted the averaged energy spectra and corresponding redistribution matrices and ancillary response files. Background spectra have been extracted from columns 3 to 5. Since energy spectra obtained from EPIC/pn fast-readout mode data are known to show excess emission below ∼1 keV (see e. g. Martocchia et al. 2006) we limited our spectral studies to energies above 0.8 keV. We fit the averaged EPIC/pn spectra within ISIS V. 1.6.2 (Houck & Denicola 2000) in the $0.8 - 10$ keV range, grouping the data to ensure that we have at least 20 source counts in each bin. We included a systematic uncertainty of 1 per cent. We used a model consisting of an absorbed (TBABS; Wilms et al. 2000) disc blackbody plus thermal Comptonisation component (NTHCOMP; Zdziarski et al. 1996; Życki et al. 1999), including a high-energy cut-off. If needed, a Gaussian was added to attribute for emission of the Fe line at ∼6.4 keV. We included an additional Gaussian component to model the features caused by gain shift due to Charge-transfer inefficiency around 1.8 and 2.2 keV (Hiemstra et al. 2011; Díaz Trigo et al. 2014). The individual spectral parameters of GX 339-4, Swift J1753.5–0127, and GS 1354–64 are given in Table 1.

Table 1. Spectral parameters of GX 339-4, Swift J1753.5–0127, and GS 1354–64.

param.	GX 339/04	GX 339/09	Sw1753/06	Sw1753/12/2	GS1354
$\mathrm{N_{dbb}}$	40922^{+15215}_{-13085}	10825^{+5996}_{-3448}	1526^{+676}_{-771}	5526^{+1511}_{-1630}	486^{+104}_{-63}
$\mathrm{T_{in}}$ [keV]	$0.202^{+0.013}_{-0.009}$	$0.223^{+0.014}_{-0.012}$	$0.213^{+0.033}_{-0.040}$	$0.257^{+0.014}_{-0.009}$	$0.50^{+0.01}_{-0.02}$
Γ	1.65 ± 0.01	$1.53^{+0.03}_{-0.05}$	1.73 ± 0.03	$1.60^{+0.01}_{-0.06}$	$1.51^{+0.05}_{-0.03}$
$\mathrm{E_{cutoff}}$ [keV]	7.6 ± 0.2	7.4 ± 0.2	> 9.3	$7.3^{+0.1}_{-0.2}$	6.82 ± 0.08
$\mathrm{E_{fold}}$ [keV]	$17.8^{+6.5}_{-3.8}$	$19.8^{+5.6}_{-2.4}$	–	15.4 ± 2.2	9.4 ± 0.5
χ^2_{red}	0.61	0.64	0.69	1.15	0.97

3 Covariance spectra and ratios

We derived covariance spectra following the approach described in Wilkinson & Uttley (2009). Taking a look at the PDS we selected short time scales related to the decaying part of the PDS, and long time scales related to the top-flat part. As reference band we used the energy range between 1 and 4 keV, taking care to exclude energies from the reference band that are in the channel of interest. To investigate the variability in a model independent way, we derived covariance ratios by dividing the long timescale covariance spectrum by the short timescale one.

The covariance ratios of GX 339-4 and Swift J1753.5–0125 are shown in Fig.1. At soft energies (below 1 keV) an increase of the ratio with decreasing energy is visible. This increase has been interpreted as the sign of additional disc variability on longer timescales (Wilkinson & Uttley 2009). The covariance ratio of GS 1354–64

(Fig.2 left panel) is flat at energies above 1 keV, while at lower energies it decreases with decreasing energy. This behaviour clearly differs from the increase of the covariance ratio towards lower energies, which has been found in later phases of the LHS in GX 339-4 and Swift J1753.5-0125. The covariance ratios observed in the 2008 and 2014 outbursts of H 1743-322 are rather flat (Fig.2 right panel).

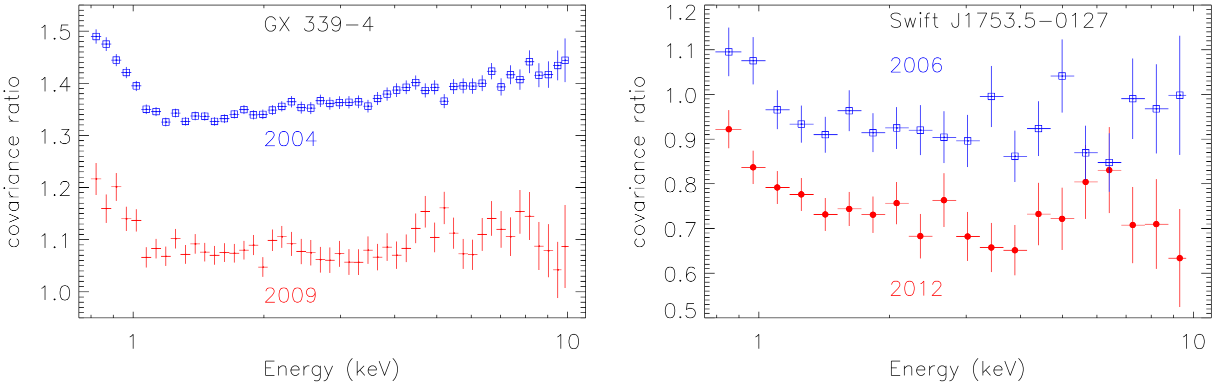

Fig. 1. Covariance ratios obtained in the LHS during outburst rise of GX 339-4 (**left**) and Swift J1753.5-0125 (**right**). The ratios show an increase towards lower energies, interpreted as sign of additional disc variability on longer time scales.

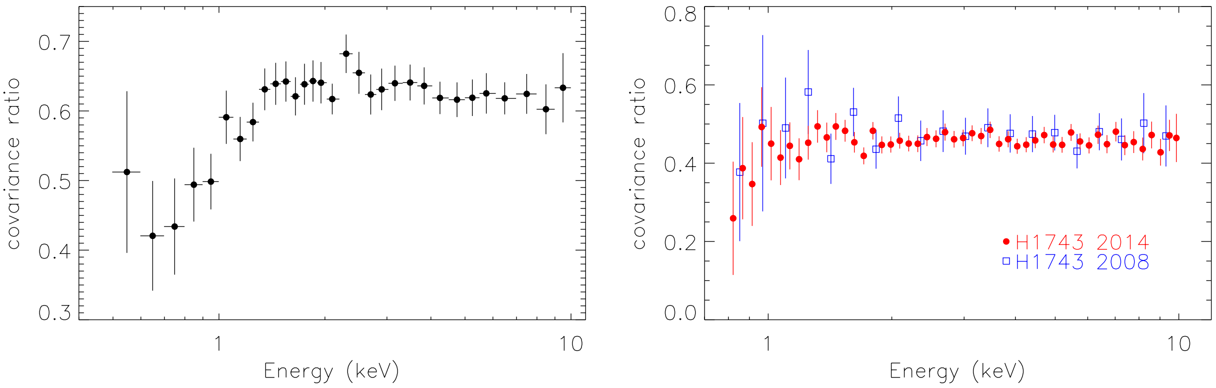

Fig. 2. Covariance ratios obtained during "failed" outbursts of GS 1354–64 (**left**) and H 1743-322 (**right**). These ratios do *not* show an increase towards lower energies.

4 Discussion

We used *XMM-Newton*/EPIC pn timing mode data of a sample of BHBs to study variability on different time scales and energy ranges using covariance spectra.

The covariance ratio obtained from the *XMM-Newton* observation of GS 1354–64 decreases with decreasing energy below 1 keV (Stiele & Kong 2016), while the one obtained for LHS observations of GX 339–4 and Swift J1753.5–0125 increases with decreasing energy (Wilkinson & Uttley 2009; Stiele & Yu 2015). The increase of the covariance ratio towards lower energies has been interpreted as a sign of additional disc variability on longer timescales. Thus the decrease observed in GS 1354–64 can be either regarded as a sign of missing disc variability on longer timescales or as a sign of additional variability on short timescales. For two observations of H 1743-322 taken during the 2008 and 2014 "failed" outbursts we also found covariance ratios that do not show an increase at lower energies. In case of H 1743-322 the covariance ratios remained rather flat (Stiele & Yu 2016).

Fitting the energy spectra in the $0.8-10$ keV range with the model given in Sect. 2, we found that the energy spectrum of GS 1354–64 differed significantly from the ones of GX 339-4 and Swift J1753.5–0125 (Stiele

& Kong 2016). The inner disc temperature of GS 1354–64 is significantly higher than the temperatures found in the previous study, while the disc blackbody normalisation, photon index, and cut-off and fold energies are lower. With a higher inner disc temperature and a smaller inner disc radius the observed covariance ratio cannot be explained by a faint disc component and it is more likely that the differences in covariance ratio are related to some changes in the accretion process. We note that all three observations that do not show increasing covariance ratio towards lower energies have energy spectra that require a rather low photon index and were taken during “failed” outbursts. Therefore different shapes of covariance ratio, although observed at soft energies, might be driven by changes in the Comptonizing component or they indicate changes in the accretion geometry that determine if a BHB goes into a “normal” or “failed” outburst. We want to mention that in the case of H 1743-322 the different shape of the covariance ratio can also be related to the higher inclination angle of this source in comparison to the inclination of GX 339–4 or Swift J1753.5-0125 (Stiele & Yu 2016). For GS 1354–64 the inclination angle is not known.

A further investigation of these different possibilities must be the aim of future studies as more data are needed. Further insight can be obtained by observations of other sources during a “failed” outburst or at high inclination to extent the size of the sample or by an observation of H 1743-322 in an early LHS during a “normal” outburst with *XMM-Newton*.

This work is based on observations obtained with *XMM-Newton*, an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA. Data used in this work are available from the *XMM-Newton* Science Archive (http://www.cosmos.esa.int/web/xmm-newton/xsa). This work was supported by the National Natural Science Foundation of China under grant Nos. 11073043, 11333005, and 11350110498, by Strategic Priority Research Program "The Emergence of Cosmological Structures" under grant No. XDB09000000 and the XTP project under grant No. XDA04060604, by the Shanghai Astronomical Observatory Key Project and by the Chinese Academy of Sciences Fellowship for Young International Scientists Grant. This project was supported by the Ministry of Science and Technology of the Republic of China (Taiwan) through grants 103-2628-M-007-003-MY3 and 104-281-M-007-060.

References

Belloni, T. & Hasinger, G. 1990, A&A, 227, L33

Belloni, T., Psaltis, D., & van der Klis, M. 2002, ApJ, 572, 392

Belloni, T. M. 2010, in Lecture Notes in Physics, Berlin Springer Verlag, Vol. 794, Lecture Notes in Physics, Berlin Springer Verlag, ed. T. Belloni, 53

Capitanio, F., Belloni, T., Del Santo, M., & Ubertini, P. 2009, MNRAS, 398, 1194

Díaz Trigo, M., Migliari, S., Miller-Jones, J. C. A., & Guainazzi, M. 2014, A&A, 571, A76

Hiemstra, B., Méndez, M., Done, C., et al. 2011, MNRAS, 411, 137

Houck, J. C. & Denicola, L. A. 2000, in Astronomical Society of the Pacific Conference Series, Vol. 216, Astronomical Data Analysis Software and Systems IX, ed. N. Manset, C. Veillet, & D. Crabtree, 591

Leahy, D. A., Elsner, R. F., & Weisskopf, M. C. 1983, ApJ, 272, 256

Martocchia, A., Matt, G., Belloni, T., et al. 2006, A&A, 448, 677

McClintock, J. E. & Remillard, R. A. 2006, Black hole binaries (Compact stellar X-ray sources), 157–213

Motta, S., Muñoz-Darias, T., & Belloni, T. 2010, MNRAS, 408, 1796

Stiele, H. & Kong, A. K. H. 2016, MNRAS, 459, 4038

Stiele, H. & Yu, W. 2014, MNRAS, 441, 1177

Stiele, H. & Yu, W. 2015, MNRAS, 452, 3666

Stiele, H. & Yu, W. 2016, MNRAS, 460, 1946

Wilkinson, T. & Uttley, P. 2009, MNRAS, 397, 666

Wilms, J., Allen, A., & McCray, R. 2000, ApJ, 542, 914

Yu, W. & Zhang, W. 2013, ApJ, 770, 135

Zdziarski, A. A., Johnson, W. N., & Magdziarz, P. 1996, MNRAS, 283, 193

Zhang, W., Jahoda, K., Swank, J. H., Morgan, E. H., & Giles, A. B. 1995, ApJ, 449, 930

Życki, P. T., Done, C., & Smith, D. A. 1999, MNRAS, 309, 561