SF2A 2018
P. Di Matteo, F. Billebaud, F. Herpin, N. Lagarde, J.-B. Marquette, A. Robin, O. Venot (eds)

THE LONG OUTBURST OF THE BLACK HOLE TRANSIENT GRS 1716–249

T. Bassi[1,2,3], M. Del Santo[1], A. D'Aì[1], S.E. Motta[4], J. Malzac[3], A. Segreto[1], J.C.A. Miller-Jones[5], P. Atri[5], R.M. Plotkin[5], T.M. Belloni[6], T. Mineo[1] and A.K. Tzioumis[7]

Abstract. We report on the multi-frequency study of the black hole transient GRS 1716–249 during the 2016-2017 outburst, after 23 years in quiescence. GRS 1716–249 was observed with the *Neil Gehrels Swift Observatory* from December 2016 until October 2017. In addition we triggered an INTEGRAL ToO combined with radio and infrared observations during the hard spectral state of the source. We have analysed all XRT and BAT data available. The X-ray hardness ratio and timing evolution indicate that the source spectrum became softer three times during the outburst. During these events, the broad band spectral modeling, performed with a thermal Comptonization plus a multicolor disk blackbody, showed spectral parameters characteristic of the hard intermediate state, also in agreement with the root mean square amplitude of the flux variability. Moreover, we present preliminary results of the spectral energy distribution modeling of GRS 1716–249 in the framework of the compact jet internal shock model.

Keywords: X-rays: general – accretion, accretion disc – black hole – X-rays: binaries – stars: jet

1 Introduction

During their outbursts the black hole transients (BHTs) can show different X-ray spectral states, characterized by different luminosities (low or high), spectral shapes (hard or soft; Zdziarski & Gierliński 2004) and timing properties (Belloni & Motta 2016). The two main spectral states are the hard state (HS) and the soft state (SS). They are usually explained in terms of changes in the geometry of the accretion flow onto the central object (Done et al. 2007). The HS spectrum is dominated by a hard X-ray power-law (Γ <2) interpreted as thermal Comptonization due to Compton up-scattering of soft disc photons by a hot electrons plasma ($\sim$100 keV) located close to the BH (Zdziarski & Gierliński 2004). It is observed also a weak thermal component that it is usually associated at a truncated accretion disc (Done et al. 2007). While, the SS spectrum shows a strong soft thermal component ($\sim$1 keV) associated to the Shakura-Sunyaev disc extending down to the innermost stable circular orbit (ISCO). Then, two further spectral states with spectral parameter in between those of the main states are also defined: the Hard and Soft Intermediate States (HIMS and SIMS, respectively, see e.g. Belloni & Motta 2016).

The identification of the different spectral state is also based on the properties of the Power Density Spectra in terms of fractional root mean squared (*rms*) variability (Muñoz-Darias et al. 2011). Moreover, the different spectral state are located in different positions on the typical q-shape pattern of the Hardness-Intensity Diagram (HID, Homan & Belloni 2005). Recently, it is observed that a number of sources do not reproduce this q-track, i.e they show only the transition HS-to-HIMS (Capitanio et al. 2009; Ferrigno et al. 2012; Del Santo et al. 2016).

The HS is typically associated with a *compact* jet. Its emission is observed mainly in the radio band and is coupled to the accretion flow, even though the nature of this connection is still unclear. For several BHTs a

[1] INAF – Istituto di Astrofisica Spaziale e Fisica Cosmica di Palermo, Via Ugo La Malfa 153, I-90146 Palermo,Italia;
[2] Universitá degli Studi di Palermo, Dipartimento di Fisica e Chimica, via Archirafi 36, I-90123 Palermo, Italia
[3] IRAP, Université de Toulouse, CNRS, UPS, CNES, Toulouse, France
[4] Department of Physics, Astrophysics, University of Oxford, Denys Wilkinson Building, Keble Road, OX1 3RH Oxford, UK 0000-0002-6154-5843
[5] International Centre for Radio Astronomy Research – Curtin University, GPO Box U1987, Perth, WA 6845, Australia
[6] INAF – Osservatorio Astronomico di Brera, via E. Bianchi 46, I-23807, Merate
[7] CSIRO Astronomy and Space Science, Australia Telescope National Facility, PO Box 76, Epping, NSW 1710, Australia

non linear radio/X-ray correlation, $F_R \propto F_X^a$ is observed, where a $\sim$0.5–0.7, and F_R and F_X are the radio and X-ray fluxes, respectively (Corbel et al. 2003; Gallo et al. 2003). In the recent years, a number of Galactic BHTs ("outliers" or radio-quiet) were found to have a steeper radio/X-ray correlation index (a $\sim$1.4 Coriat et al. 2011).

The BH X-ray transient GRS 1716–249 was detected in outburst on 2016 December 18 after more than twenty years in quiescence (Negoro et al. 2016). It was observed with XRT and BAT instruments on board the *Neil Gehrels Swift Observatory* (hereafter *Swift*). Then, it was performed a multi-wavelength campaign on 2017 February 9. The *Swift* spectral and timing analysis results on the 2016-2017 outburst of GRS 1716–249 are reported in Bassi et al. (2018). Here we briefly present the main results of that paper and preliminary results on the modelling of the spectral energy distribution (SED) of GRS 1716–249.

2 Results and Discussion

GRS 1716–249 increases the sample of the known BHTs that have shown "failed" state transition outbursts, during which the source does not complete the full pattern in the HID. Despite of the three softening events that occurred during the outburst (Fig. 1, left panel), GRS 1716–249 did not make the transition to the canonical soft state (neither to the SIMS). Figure 1 (right top panel) shows the total 0.5–10 keV count rate versus the count rate ratio 2–10 keV/0.5–2 keV. It is worth noting that the XRT monitoring started a few days after the hard X-ray peak, therefore the HS right-hand branch in the HID was missed and the GRS 1716–249 q-track starts from the bright HS. The X-ray spectra of GRS 1716–249 are observed to soften and harden twice along the intermediate states branch, until to the softer state observed (magenta square). Then the flux starts to decrease and the source simultaneously becomes harder along a diagonal track. The shape of the HID differs from that has been observed in the majority of BHTs (e.g. GX 339-4, Belloni et al. 2006): i.e. GRS 1716–249 does not show a clear SS branch on the left side of the diagram as observed in H 1743–322 and MAXI J1836–194 (Capitanio et al. 2009 and Ferrigno et al. 2012, respectively).

The values of the *rms* variability amplitude are related to the spectral states of BHTs. After the beginning of the outburst of GRS 1716–249, we have observed that the fractional *rms* variability amplitude is between 25-30%, typical of the HIMS (Muñoz-Darias et al. 2011, see Fig. 1 left bottom panel). Simultaneously with the third HR softening (Fig. 1, left b panel), the fractional *rms* decreased down to 12% without drop below the typical values of the SS ($\leq$5%).

Then, we observed that the disc luminosity never dominates the emission of the source. The softer broadband XRT and BAT spectra were fitted with an absorbed thermal Comptonisation plus a multi-colored disc blackbody model. In the softer episodes the spectra show a significant weak soft thermal component ($kT_{in}\simeq$0.2-0.5 keV) with a maximum disc flux contribution of about 34% to the total unabsorbed bolometric flux. In addition, we have used the DISKBB normalization to estimate the inner disc radius. Most of our measurements are consistent with a constant radius $R_c \sim$15 km and with a disc luminosity which is bound to the inner disc temperature according to $L \propto T^4$. This suggests that the inner disc might have reached the ISCO during the three softening episodes even-though the source was in the HIMS. Another possibility is that in the intermediate state the hot accretion flow may re-condensate into a mini-disc as predicted by the disc/corona condensation evaporation models (Meyer-Hofmeister et al. 2009).

Assuming an upper limit on the inclination angle of $\vartheta <60^\circ$ (Frank et al. 1987), a lower limit on the BH mass of $M_{BH} >4.9\,M_\odot$ (Masetti et al. 1996) and the measured inner disc radius R_c, we estimated an upper limit on the ISCO radius of $3\,R_g$. Therefore, we could argue that the black hole in GRS 1716–249 would be rotating with an estimated spin lower limit of $a_* >0.8$ (with a_* the dimensionless spin).

An important tool to investigate the emission properties of BHTs is the radio/X-ray correlation. Coriat et al. (2011) suggested that the correlation of the "outliers" would be produced by a radiatively efficient accretion flow ($L_X \propto \dot{M}$), while the radio-loud branch ($L_R \propto L_X^{0.6}$) would result from inefficient accretion ($L_X \propto \dot{M}^{2-3}$). GRS 1716–249 is located on the steeper branch and it increase the number of radio-quiet BHTs (Fig. 2, left panel). Recently, another explanation on the origin of these two classes of sources was proposed by Espinasse & Fender (2018). They found that radio-quiet sources tend to have a negative spectral index α ($S_\nu \propto \nu^\alpha$) while for the radio-loud sources a positive α was observed. This could suggests different core jet properties (rather than accretion flow) for radio-quiet and radio-loud sources. The radio spectral indices measured of the GRS 1716–249 are consistent with a flat-spectrum compact jet and they are within the statistical distribution of the radio-quiet slope reported by Espinasse & Fender (2018).

3 Modeling the multi-wavelength SED

Modeling the SEDs of BHTs provides information on the nature of the sources emission, their physical parameters, i.e. the size of the emitting region, the magnitude of the magnetic field, and in particular the nature and the interaction between the various components, such as the corona and the jet. An *INTEGRAL* ToO, combined with simultaneous radio and infrared observations on GRS 1716–249, was performed on 2017 February in order to investigate each radiative component and compare the data with the different radiative models.
The broadband spectrum in HS, including also the SPI/*INTEGRAL* data, shows a non-thermal excess at high energies with respect to the absorbed thermal Comptonization model adopted when using only XRT and BAT data. In order to investigate the origin of this non-thermal component we fitted the SED of the accretion flow emission with an irradiated disc plus Comptonization model and the jet emission with the compact jet internal shock model (Malzac 2014). Even though we have obtained a good fit with acceptable jet and accretion flow parameters, our preliminary results show that the jet component does not explain the non-thermal excess observed (Fig. 2, right panel). It is worth noting that in this fit the slope of the electron energy distribution in the jet model was frozen at 2.5. A jet with a harder electron distribution would explain the high energy excess observed. Further studies on this issue are ongoing.

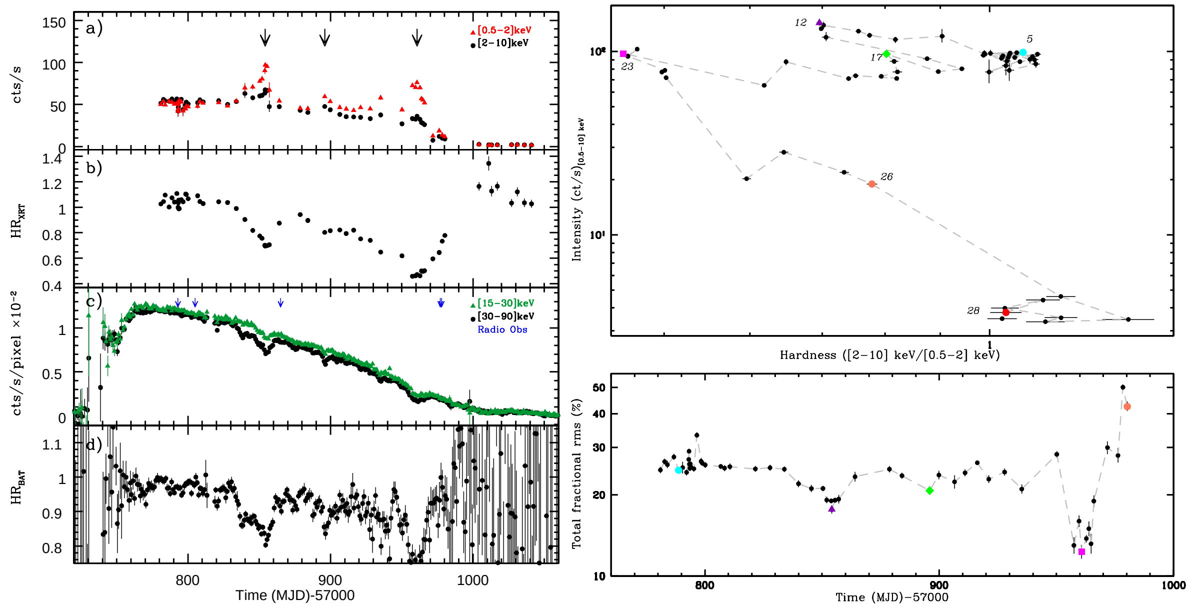

Fig. 1. Left: XRT light curves in the 0.5–2 keV and 2–10 keV energy ranges, extracted by pointing (panel *a*), plotted with the corresponding hardness ratio (panel *b*). In panel *c*, we show the 15–30 keV and 30–90 keV light curves observed by BAT, with a 1-day binning time, and the related hardness ratio (panel *d*). In the XRT light curve, three strong peaks (black arrows) in correspondence to dips in the BAT light curve and in the hardness ratios have been observed. These indicate softening in the X-ray spectra. **Upper Right:** Hardness-Intensity Diagram. The outburst has been observed by XRT when GRS 1716–249 was at the top-right side of the pattern (cyan dot), then it evolves along the horizontal branch (purple triangle). It reaches the softest state (magenta square) and then takes a diagonal trajectory (orange dot) on its return to the hard state (red dot), before going in quiescence. The magenta square, purple triangle, and green diamond correspond to the softest points in each of the three softening episodes. **Lower Right:** XRT fractional *rms* evolution. The soft points observed in the HID correspond to fractional *rms* values typical of the HIMS (10%-30%, Muñoz-Darias et al. 2011).

4 Conclusions

We have presented the X-ray spectral and timing analysis of the BHT GRS 1716–249 during its 2016-2017 outburst. GRS 1716–249 can be added to the sample of BHTs that show a "failed" state transition outburst. The timing results and spectral parameters evolution show that the source was in the HIMS during the spectral softening episodes observed. Moreover, our results suggest that either the inner disc might have reached the

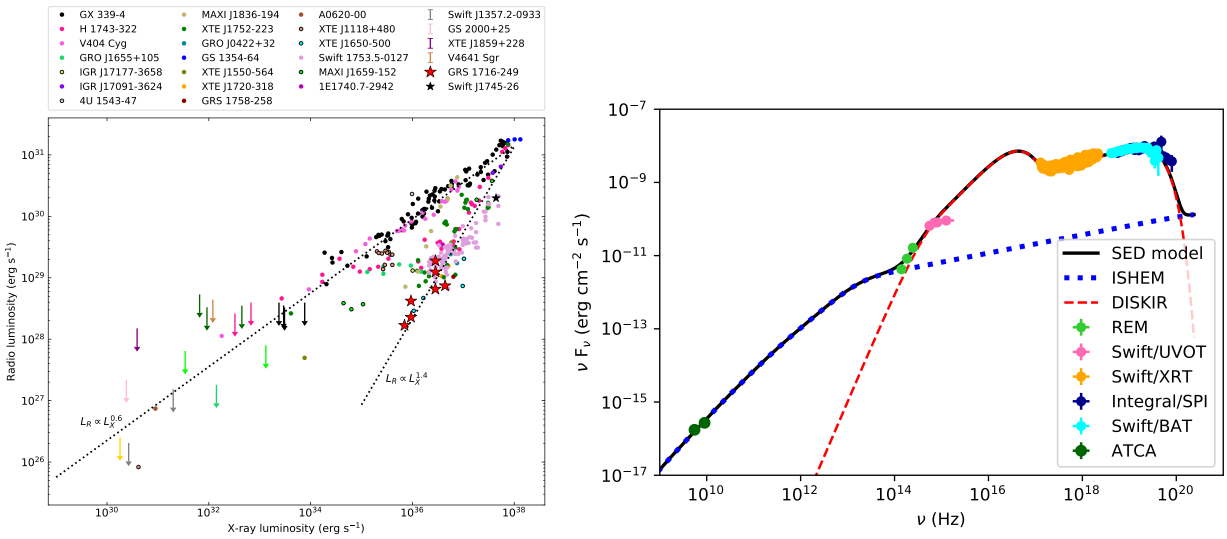

Fig. 2. Left: Radio/X-ray luminosity correlation. The X-ray luminosities and the radio observations are from Bahramian et al. 2018. The X-ray luminosities are calculated in the 1-10 keV energy range and the radio observations are converted to the 5 GHz common frequency. GRS 1716–249 (red stars) is located on the radio-quiet branch. **Right:** The observed SED of GRS 1716–249 fitted with a disc plus thermal Comptonization plus compact jet internal shock model. Preliminary results show that the jet does not reproduce the high energy tail observed.

ISCO during these softening episodes, or the hot accretion flow might re-condensate in an inner mini-disc. The GRS 1716–249 system seems to host a rapidly rotating BH with $a_* > 0.8$. Finally, we have located GRS 1716–249 on the radio-quiet branch in the radio/X-ray luminosity plane.

We refer the interested readers to Bassi et al. (2018) for a more comprehensive and detailed discussion.

We acknowledge financial contribution from the agreement ASI-INAF n.2017-14-H.0 and funding from the European Unions Horizon 2020 Programme under the AHEAD project (grant agreement nr. 654215).

References

Bahramian, A., Miller-Jones, J., Strader, J., et al. 2018, Radio/X-ray correlation database for X-ray binaries

Bassi, T., Del Santo, M., D'Ai, A., et al. 2018, MNRAS

Belloni, T., Parolin, I., Del Santo, M., et al. 2006, MNRAS, 367, 1113

Belloni, T. M. & Motta, S. E. 2016, in Astrophysics and Space Science Library, Vol. 440, Astrophysics of Black Holes: From Fundamental Aspects to Latest Developments, ed. C. Bambi, 61

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

Corbel, S., Nowak, M. A., Fender, R. P., Tzioumis, A. K., & Markoff, S. 2003, A&A, 400, 1007

Coriat, M., Corbel, S., Prat, L., et al. 2011, MNRAS, 414, 677

Del Santo, M., Belloni, T. M., Tomsick, J. A., et al. 2016, MNRAS, 456, 3585

Done, C., Gierliński, M., & Kubota, A. 2007, A&A Rev., 15, 1

Espinasse, M. & Fender, R. 2018, MNRAS, 473, 4122

Ferrigno, C., Bozzo, E., Del Santo, M., & Capitanio, F. 2012, A&A, 537, L7

Frank, J., King, A. R., & Lasota, J.-P. 1987, A&A, 178, 137

Gallo, E., Fender, R. P., & Pooley, G. G. 2003, MNRAS, 344, 60

Homan, J. & Belloni, T. 2005, Ap&SS, 300, 107

Malzac, J. 2014, MNRAS, 443, 299

Masetti, N., Bianchini, A., Bonibaker, J., della Valle, M., & Vio, R. 1996, A&A, 314, 123

Meyer-Hofmeister, E., Liu, B. F., & Meyer, F. 2009, A&A, 508, 329

Muñoz-Darias, T., Motta, S., & Belloni, T. M. 2011, MNRAS, 410, 679

Negoro, H., Masumitsu, T., Kawase, T., et al. 2016, The Astronomer's Telegram, 9876

Zdziarski, A. A. & Gierliński, M. 2004, Progress of Theoretical Physics Supplement, 155, 99