PROCEEDINGS OF SCIENCE

Low/hard state of microquasars at low luminosities

Tolga Dinçer* **and Emrah Kalemci**
Sabancı University, Orhanlı-Tuzla, 34956, Istanbul, TURKEY
E-mail: tdincer@su.sabanciuniv.edu
E-mail: ekalemci@sabanciuniv.edu

John A. Tomsick

SSL, 7 Gauss Way, University of California, Berkeley, CA 94720-7450, USA

Michelle Buxton

Department of Astronomy, Yale University, P.O. Box 208101, New Haven, CT 06520, USA

Galactic black hole transients (GBHTs) spend most of their time in the low/hard spectral state during the outburst decay. This state exhibits a hard X-ray spectrum, with X-ray flux correlating with the radio and sometimes the optical/infrared flux. The radio and some part of the infrared emission comes from a compact jet. Understanding the interplay between X-ray emission and jet properties is very important in understanding the accretion geometry in the hard state. As the luminosity declines, the spectra of the GBHTs get harder. However, for a few sources at very low luminosity levels a softening of the spectrum has been observed. In this work, our motivation is to discuss the evolution of GBHTs at the very lowest luminosity levels using *RXTE* data and compare with evolution of the radio and the optical/infrared fluxes. We discuss the possible reasons for softening and whether the softening is related to the jet emission.

VII Microquasar Workshop: Microquasars and Beyond
September 1-5 2008
Foca, Izmir, Turkey

*Speaker.

1. Introduction

Depending on the X-ray spectral and temporal properties, the outburst evolution of GBHTs is characterized with various X-ray spectral states (see [21] for a review). One of those, the low/hard state, mostly governs the outburst rise and decay even though a few exceptions (e.g., SWIFT J1753.5-0127, [1]) have been observed. When the X-ray activity decreases significantly, the source enters into a quiescent state. The X-ray spectrum in the low/hard state is usually modelled using a power law component which is thought to be related to Comptonization of cold photons in a hot plasma, synchrotron emission coming from outflow of matter through a jet, or an advective dominated flow, all having a total contribution of at least 80% or more, and a weak thermal component associated with the emission coming from the inner hot accretion disk. An iron line representing the reflection may also be needed. The quiescent state resembles the low/hard state in terms of spectral and temporal properties at low luminosity levels [27].

Multiwavelegth observations during the low/hard state have provided a better understanding of the nature of GBHTs. Jets are sometimes spatially resolved in radio, and the radio activity is also related to the launch of jets. Global radio/X-ray correlations have been established [6, 10]. The optical/infrared(OIR) emission on the other hand could originate from the companion star, the disk, the jet [17, 5] or reprocessing of X-rays. An X-ray/OIR correlation has also been suggested [24]. But, lately some exceptions have been observed against the X-ray/radio and X-ray/OIR correlations [3, 4, 23, 25].

The general picture of outburst evolution decay of black holes has been summarized in [16]. This work points out that for jets to reappear in the radio or OIR, the X-ray spectrum must reach a threshold hardness. Also, towards the end of the decay, a softening of the spectrum is possible. Softening of the spectrum has been observed during quiescent state of black holes with X-ray imaging instruments [7, 8]. In this work, we will focus on the decay evolution of GBHTs at the very lowest luminosity levels using *RXTE* data and discuss the behavior of the X-ray spectrum, as well as the OIR behavior.

2. Observations and Data Analysis

In this work, we analyzed the *RXTE* and the *SMARTS* OIR monitoring observations to study the long term outburst decay evolution of GBHTs in the low/hard state. For some sources, we used readily available information from the literature. In order to see whether the sources in our sample exhibit a softening during the decay, we reanalyzed some of the *RXTE* data with great care to take out the diffuse Galactic ridge emission.

We used 3-25 keV band of the PCA instrument, and added 0.8% up to 7 keV, and 0.4% above 7 keV as systematic error. Since we deal with the lowest fluxes, diffuse Galactic ridge emission becomes significant. In order to model the ridge emission we used simultaneous observations of imaging instruments, quiescent state observations, or the literature [22]. In addition, OIR and radio data were gathered.

X-ray spectral fitting of each observation is made using a common model consisting of interstellar absorption, a multicolor disk black body, a smeared edge [9], a power law, and a model representing the ridge emission if necessary (power law plus a Gaussian).

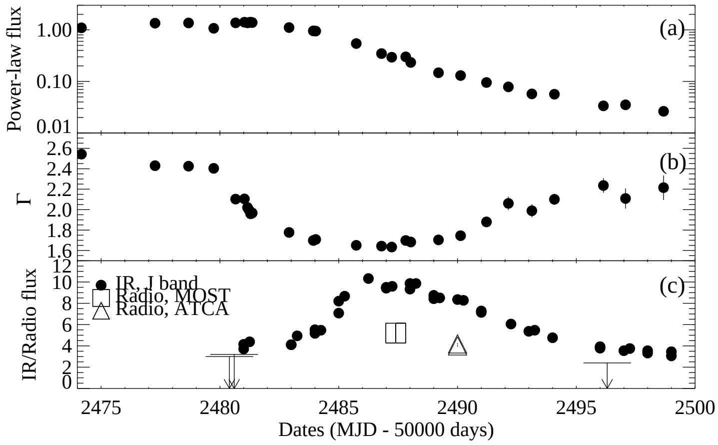

Figure 1: 2002 outburst decay of 4U 1543-47 replotted from Kalemci et al. 2005; the evolution of (a) the power law flux in 3-25 keV band in units of 10^{-9} ergs cm^{-2} s^{-1}, (b) the photon index, (c) the J-band fluxes from Buxton et al. 2004 along with radio fluxes from our observations (triangles) and Park et al. 2004. (upper limits and square)

3. Results

3.1 4U 1543-47

The details of long term multiwavelength coverage and analysis of the 2002 outburst decay of the source can be found in [15]. The Galactic ridge emission was modelled using the description introduced in [22]. Figure 1 shows the evolution of spectral parameters along J-band and radio flux that belongs to intermediate state and low/hard state. As the flux drops, photon index decreases and J-band flux and radio activity increase. When the photon index reaches its hardest value, J-band emission peaks (see Fig. 1 in [2]). Afterwards, the decrease in X-ray flux and J-band is accompanied with an increase in photon index.

3.2 GRO J1655-40

The long term multiwavelength coverage of 2005 outburst decay of the source is published in [16] excluding the lowest flux analysis. We analyzed the very end of the outburst decay taking into account the ridge emission. The Galactic ridge emission was modelled using simultaneous *RXTE* and *SWIFT* observations when the source was faint [12]. Figure 2 shows the evolution of spectral parameters along J-band magnitude and radio flux right after the radio activity begins. In the low/hard state while the X-ray flux and J-band magnitude are dropping, the photon index gradually increases.

3.3 GX 339-4

Figure 3 shows the long term evolution of spectral parameters and J-band magnitude in the low/hard state in the 2007 outburst. The Galactic ridge emission was modelled using simultaneous *RXTE* and *CHANDRA* observations when the source was faint [11]. During the decay, while photon index was fluctuating, a rebrightening in X-rays have been observed. The J-band magnitude starts to increase before the X-ray rebrightening. Towards the end of the decay the photon index increases.

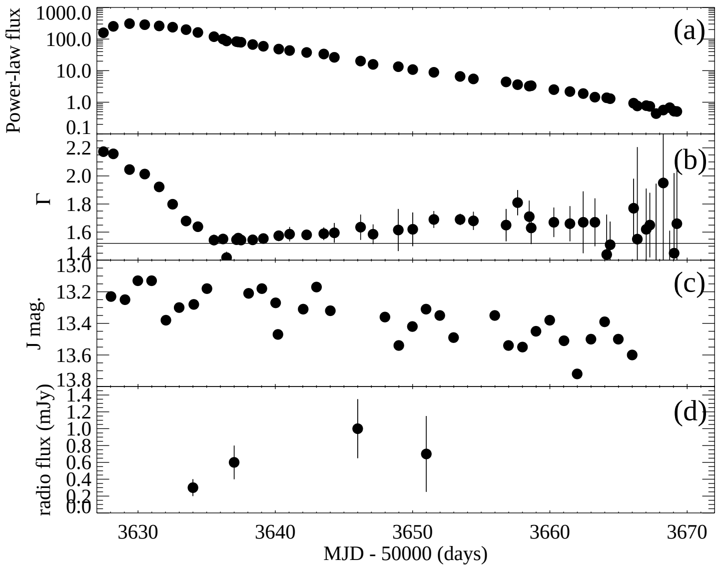

Figure 2: 2005 outburst decay of GRO J1655-40; the evolution of (a) the power law flux in 3-25 keV band in units of 10^{-11} ergs cm^{-2} s^{-1}, (b) the photon index, (c) the J-band magnitude, (d) the radio flux.

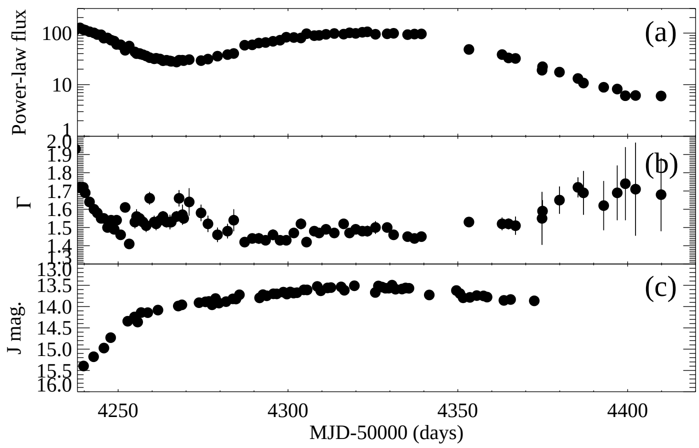

Figure 3: 2007 outburst decay of GX 339-4; the evolution of (a) the power law flux in 3-25 keV band in units of 10^{-9} ergs cm^{-2} s^{-1} , (b) the photon index, (c) the J-band magnitude.

3.4 XTE J1550-564

In 2000, XTE J1550-564 showed an outburst and a minioutburst in 2001. X-ray spectral analysis of 2000 outburst decay is studied by [26, 14]. We used readily available analysis of Kalemci Ph.D. Thesis (2002). Figure 4 belongs to the 2000 outburst decay when the source is in the low/hard state. At the beginning of the decay, the photon index drops whereas the H-band magnitude is almost flat. Towards the end of the decay the photon index stays almost flat and H-band IR magnitude increases. The X-ray flux do not respond to flaring in H-band. During the 2002 minioutburst, only result that is available in Figure 5 is the smooth increase of the photon index towards the end of the decay.

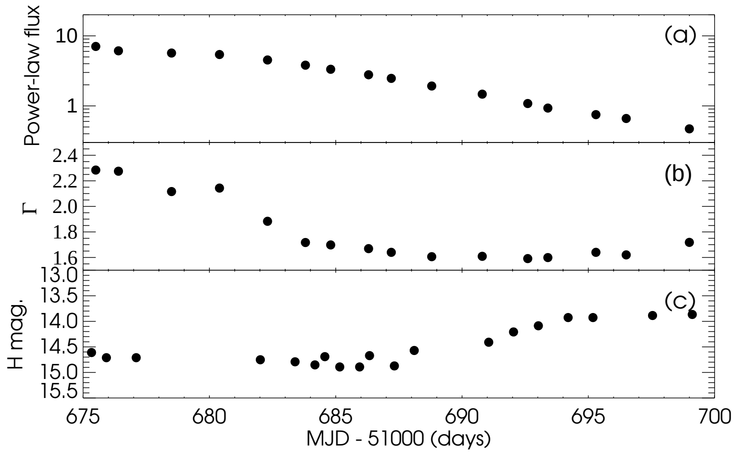

Figure 4: 2000 outburst decay of XTE J1550-564; the evolution of (a) the power law flux in 2.5-20 keV band in units of 10^{-9} ergs cm^{-2} s^{-1} , (b) the photon index, (c) the H-band magnitude.

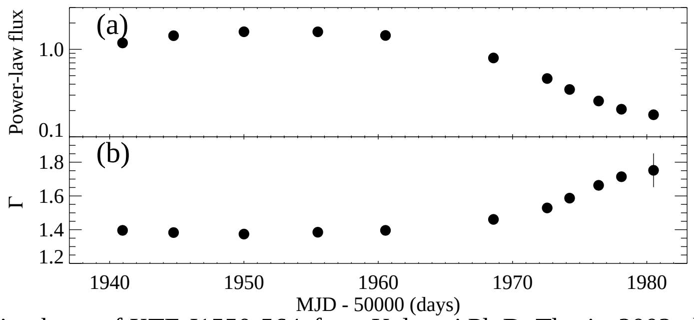

Figure 5: 2001 minioutburst of XTE J1550-564, from Kalemci Ph.D. Thesis, 2002; the evolution of (a) the power law flux in 3-25 keV band in units of 10^{-9} ergs cm^{-2} s^{-1} , (b) the photon index.

3.5 SWIFT J1753.5-0127

SWIFT J1753.5-0127 is an interesting black hole which has not been observed in any other state than the low/hard state during its outbursts. In 2005 July a thermal component was found during the decay [20]. Figure 6, which shows the evolution of spectral parameters during the 2005 outburst decay, is taken from [20]. This source again shows an increase in the photon index towards the end of the outburst.

3.6 Summary of Results

- Except GRO J1655-40, all sources observed with the *SMARTS* in our sample show a secondary outburst in the OIR.

- It is possible that the OIR emission from the jet of GRO J1655-40 is buried under emission coming from the companion.

- There is no response in the X-ray flux to the increase in the OIR emission.

- There is a softening of the X-ray spectrum for many sources towards the end of the outburst. For some sources the softening starts right after the appearance of the jet.

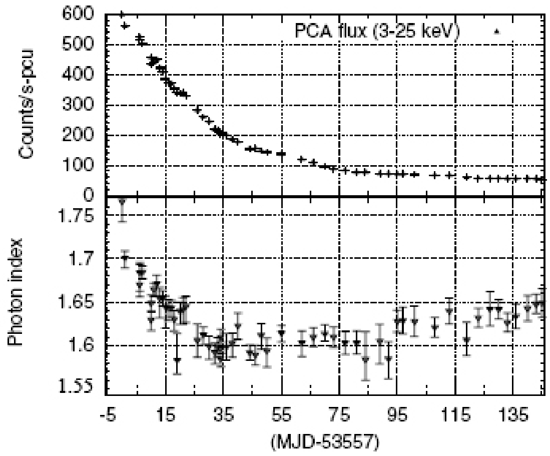

Figure 6: 2005 outburst decay of SWIFT J1753.5-0127, taken from Ramadevi and Seetha 2007; the evolution of (a) PCA count rate in 3-25 keV band, (b) the photon index.

4. Discussion

The softening of the X-ray spectrum towards the end of outbursts is detected with the *RXTE* for most of the sources in our sample (see also, Wu, Q. and Gu, M. PoS(MQW7)064). Here, we discuss possible reasons of this softening.

If we assume a simple disk-corona picture, the power-law-like hard X-ray spectrum is created by the Comptonization process. The photon index then depends on the Compton y-parameter which depends on the electron temperature and the optical thickness of the medium. Therefore, a decrease in optical depth due to a change in the corona size, decrease of mass accretion rate, or decrease of evaporation rate might cause a softer spectrum. A decrease in the coronal temperature might also lead to a softer spectrum. Cooling of the corona may be caused by an additional soft component from the jet or by energy transfer from the corona to the jet.

Even though there are well established connections between jet emission and X-rays, such as correlations and the threshold hardness for the jet reappearance, whether jets affect the X-ray emission afterwards is less clear for the datasets we analyzed. The sources 4U 1543-47, GX 339-4 and XTE J1550-564 in our sample, show a secondary outburst in OIR whereas for GRO J1655-40 the OIR magnitude decreases during the decay while it is detected in the radio. The second peak is interpreted as synchrotron emission from the jet. GRO J1655-40 has an early spectral type companion star therefore it is possible that the OIR emission is suppressed under emission coming from the companion. This possibility is also confirmed with a broadband spectra fitting using a jet model [18]. It is worth mentioning that if a relation between the jet and softening exists, the timing of such a softening is not consistent in all our sources. At times, softening occurs at the peak of OIR or radio emission (e.g, 4U 1543-47, GX 339-4), while at other times it occurs at the beginning of OIR or radio activity (e.g, GRO J1655-40).

In conclusion, we presented the possible reasons of the softening based on the observational X-ray spectral properties, OIR and radio fluxes. We clearly need to increase the sample of sources with good OIR/radio coverage and softening to conclusively say anything about a relation between the jet and the softening.

Acknowledgments

This work is supported by TÜBİTAK Career Grant 106T570. EK acknowledges the support of Turkish National Academy of Sciences (TÜBA) in the form of Young Scientist Award Programme (GEBIP) grant, and also support from the International Space Science Institute (ISSI) at Bern.

References

[1] Brocksopp, C., Bandyopadhyay, R. M., Fender, R. P., 2004, NewA, 9, 249

[2] Buxton, M. M. and Bailyn, C. D., 2004, ApJ, 615, 880

[3] Cadolle Bel M., et al., 2006, ApJ, 659, 549

[4] Chaty, S., *Multi-wavelength observations of the microquasar XTE J1720-318: a transition from high-soft to low-hard state*, in proceedings of *VI Microquasar Workshop*, PoS(MQW6)014

[5] Corbel, S. and Fender, R. R., 2002, ApJ, 573, 35

[6] Corbel, S., et al., 2003, A&A, 400, 1007

[7] Corbel, S., Tomsick, J. A., Kaaret, P., 2006, ApJ, 636, 971

[8] Corbel, S., Koerding, E., Kaaret, P., 2008, MNRAS, 389, 1697

[9] Ebisawa, K., et al., 1994, PASJ, 46, 375

[10] Gallo, E., Fender, R. P., Pooley, G. G., 2003, MNRAS, 344, 60

[11] Gallo, E., Fender, R., Corbel, S., 2003, ATel, 196, 1

[12] Homan, J., et al., 2005, ATel, 644, 1

[13] Jain, R. K., et al., 2001, 554, 181

[14] Kalemci, E., 2002, *Ph.D. Thesis*, University of California, San Diego

[15] Kalemci, E., et al., 2005, ApJ, 622, 508

[16] Kalemci, E., et al., 2006, *State transitions and jet formation in black hole binaries*, in proceedings of *VI Microquasar Workshop*, PoS(MQW6)012

[17] Markoff, S., Falcke, H., Fender, R., A&A, 2001, 372, 25

[18] Migliari, S., et al., 2007, ApJ, 670, 610

[19] Park, S. Q., et al., 2004, ApJ, 610, 378

[20] Ramadevi, M. C. and Seetha, S., 2007, MNRAS, 378, 182

[21] Remillard, R. A. and McClintock, J. E., 2006, ARA&A, 44, 49

[22] Revnivtsev, M., 2003, A&A, 410, 865

[23] Rodriguez, J., et al., 2007, ApJ, 655, 97

[24] Russell, D. M., et al., 2006, MNRAS, 371, 1334

[25] Shaposhnikov, N., et al., 2007, ApJ, 655, 434

[26] Tomsick, J. A., et al., 2001, ApJ, 563, 229

[27] Tomsick, J. A., Kalemci, E., Kaaret, P., 2004, ApJ, 601, 439

[28] Wu, Q. and Gu, M., 2008, *The Hard X-ray Spectral Evolution in X-ray Binaries, Active Galactic Nuclei and Ultraluminous X-ray Sources*, in proceedings of *VII Microquasar Workshop*, PoS(MQW7)064