Publications of the Korean Astronomical Society
30: 599 ∼ 601, 2015 September

pISSN: 1225-1534
eISSN: 2287-6936
http://dx.doi.org/10.5303/PKAS.2015.30.2.599

A STUDY OF THE DYNAMICAL CROSS CORRELATION FUNCTION IN A BLACK HOLE SOURCE XTE J1550-564

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(Received November 30, 2014; Reviced May 31, 2015; Aaccepted June 30, 2015)

ABSTRACT

The short time scale X-ray variability associated with the accretion disk around compact objects is complex and is vaguely understood. The study of the cross correlation function gives an insight into the energy dependent behavior of the variations and hence connected processes. Using high resolution *RXTE* data, we investigate the dynamical cross correlation function of an observation of a black hole source XTE J1550-564 in the steep power law state. The cross correlation between soft and hard X- ray energy bands revealed both correlated and anti-correlated delays ($\leq \pm 15$ s) on a correlation time scale of 50 s. It was noticed that the observed delays were similar to the delays between X-ray and optical/IR bands in other black hole and neutron star sources. We discuss the possible mechanisms/processes to explain the observed delays in the dynamical CCF.

Key words: accretion, accretion disk—binaries: close—stars: individual (XTE J1550-564)—X-rays: binaries

1. INTRODUCTION

The Rossi X-ray Timing Explorer (RXTE) has played a key role in deciphering various physical and radiative mechanisms in galactic black hole (BH) X-ray sources. High resolution temporal data unveiled the presence of Quasi periodic Oscillations (QPOs) from mHz to kHz ranges in BHs, which later became a fundamental parameter to constrain their masses. The spectral data of RXTE, were able to give a picture of the evolution of accretion disks during an outburst. The classification scheme of BHs viz. low-hard (LH)/hard states occurring at the onset of outburst and very high state/steep power-law (SPL)/Intermediate hard (IM) or thermal dominated (TD)/soft states occurring at the peak/slightly off-peak of an outburst, suggests that the inner front of the accretion disk moves towards the black hole from the onset of an outburst its peak (Remillard & McClintock, 2006; Done et al., 2007; Belloni et al., 2011). As the source intensity decreases gradually from the outburst, the disk returns to the low hard state. However the complete evolution during an outburst, the transition of the source from one spectral state to another, and the detailed accretion processes are not clear.

The co-evolution of energy dependent X-ray light curves associated with accretion disks is poorly understood. The study of the cross correlation function (CCF) gives an insight into the correlation strength of the energy dependence of light curves, which would unveil the various mechanisms involved in the accretion disk. Earlier studies of CCFs between soft and hard energy bands in a few black hole and neutron star sources showed anti-correlated hard/soft delays of a few tens to hundreds of seconds, though most of them were found to be correlated (Choudhury et al., 2005; Sriram et al., 2007; Lei et al., 2008; Sriram et al., 2009; Sriram et al., 2010; Sriram et al., 2012). These studies of CCFs were performed at a high Fourier time scale or correlation time scale of the order of a few hundreds to thousands seconds. These delays were attributed to the viscous time scale during which the Keplerian disk and Compton cloud were readjusted in the accretion disk. The cross spectral studies revealed another kind of delays of the order of a few micro/milli seconds, associated with the Comptonization time scale (van der Klis, 1987). The CCFs and dynamical CCFs at shorter correlation time scales between X-ray and optical/IR bands in a couple of black hole and neutron star sources show soft and hard X-ray delays $\leq$10–30 s (Petro et al., 1981; McGowan et al., 2003; Durant et al., 2011). They concluded that such delays on shorter time scales cannot be explained by simple accretion disk models and the origin is probably much more complex.

In order to understand the correlation strengths and delays on a short time scale, we study the dynamical CCF in a black hole source XTE J1550-564 in the steep power law state.

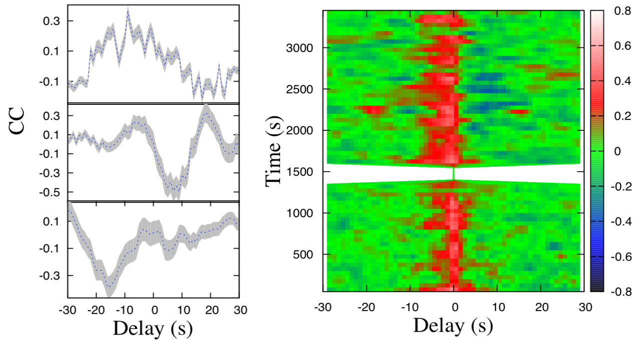

Figure 1. Left panel: A few CCFs observed in the study of dynamical CCF. The dashed line corresponds to mean CCF and gray shade marks error ranges. Right panel: Dynamical CCF between soft (2–5 keV) and hard (13–60 keV) energy bands with a bin size of 50 s. The red color shows the correlation strength and blue shows the anti-correlation strength (right panel).

2. DATA REDUCTION AND ANALYSIS

The data were obtained with the Proportional Counter Array (PCA) onboard the RXTE. The PCA consists of five proportional counter units effectively covering the X-ray energy of 2 − 60 keV (Jahoda et al., 2006). The ObsID 40401-01-58-01 (date of observation 1999-03-17) of the source XTE J1550-564 was selected to investigate the dynamical cross-correlation function (CCF). We used single bit mode and event mode data to extract the soft (2-5 keV) and hard (13-60 keV) energy band light curves in order to obtain the dynamical CCF. HEASOFT v6.8 software was used to reduce the data. We used the *crosscor* tool in the XORNOS package to extract the cross-correlation functions (Sriram et al., 2007; Sriram et al., 2011). The CCFs were often found to have complex structures, however around zero delay the function can be fitted with a Gaussian/inverted Gaussian function depending upon whether the CCF is correlated or anti-correlated. The error bars for X-ray delays were calculated at a 90% confidence level (χ^2=2.71).

Fig. 1 (right panel) shows the dynamic CCF along with the cross-correlation coefficient on a color scale. A few prominent CCFs are shown in the left panel where correlated (-15 ± 6s) and anti-correlated (8 ± 3 s & -16 ± 2 s) delays are clearly observed (top to bottom panels). The green color shows the uncorrelated features in the dynamic CCF of the right panel, red shows the correlated features and blue shows the anti-correlated features. Each bin of the dynamic CCF is about 50 s. It was observed that the number of anti-correlated CCFs are relatively low during initial 1000 s and increased later. The shape of the CCF changed continuously, which suggests that the source/sources of the variability in the accretion disk were changing on a short time scale. Most of the time, the CCFs were correlated with zero delay but on a few occasions the CCFs showed positive and negative delays of a correlated and anti-correlated nature.

3. DISCUSSION AND CONCLUSIONS

We investigated the dynamic CCF of a steep power law state observation of the black hole source XTE J1550-564. Earlier studies of CCFs were based on longer Fourier time scales (Sriram et al., 2007; Sriram et al., 2009; Sriram et al., 2012). It was found that in the case of black hole sources, the soft and hard light curves were correlated, which is a general feature, but on few occasions show an anti-correlated feature accompanied by soft/hard delays. The delays were interpreted as the small viscous time scales during which the Keplerian disk and the Compton cloud were readjusting. Similar smaller anti-correlated delays have also been observed in neutron star sources (Lei et al., 2008; Sriram et al., 2012). Much smaller delays, on the order of micro/milli seconds, were reported between different energy bands in BHs and neutron stars, which were physically associated to the reprocessing time scale for soft photons to convert into hard photons in the Compton cloud via the Comptonization process (van der Klis, 1987). Durant et al. (2011) found delays on the order of < 10 s in the CCF between optical and X-ray energy bands in two BHs and two neutron stars. They have concluded that a simple shot noise model for the production of the light curves is not sufficient, as the processes in accretion disk are complex and highly variable even at shorter time scales. Similar kinds of delays (< 30 s) were observed between X-ray and optical bands in LMC X-2 and Sco X-1 (McGowan et al., 2003; Petro et al., 1981). Recent studies of CCFs between the X-ray and IR with a correlation length of 60 s show anti-correlated delays (∼ 10 s) in the black hole source GRS 1915+105 (Lasso-Cabrera & Eikenberry, 2013). Though the wavelength is significantly different between their studies and the present study, it should be noted that delay time scales observed between X-ray and optical/IR bands and the present study, i.e. between soft and hard energy bands, are very similar to each other.

The study of dynamic CCFs helps in unveiling the complex evolution of the energy dependencies of light curves in the accretion disk around compact objects. We found correlated soft/hard delays of the order of < ± 15 s between the soft (2–5 keV) and hard (13–60 keV) energy band light curves. Occasionally, anti-correlated delays of similar magnitudes (< ±15 s) were also observed (see left panel, Fig. 1). In the truncated accretion disk scenario, the soft X-ray photons, which most probably originated from the Keplerian disk, are reprocessed in the Compton cloud, assumed to be located in the inner region of the accretion disk, and finally become Comptonized as hard X-ray photons. The dynamical CCFs were calculated with a correlation time scale of about 50 s, which is much longer than the typical Comptonization time scale. Hence, we suggest that the observed correlated delays (< ±15 s) could possibly be due to the viscous time scale as well as the Comptonization reprocessing time scale.

The other possible scenario is that soft photons are produced in the disk and get Comptonized in the jet which, is often observed in the SPL state of BHs. As the soft photons enter the base of the jet (considered to be hot), they get converted into hard photons and traverse along the jet. The CCF of these hard photons and disk soft photons could possibly explain the observed delays. Hence, it is possible that the delays are due to the contributions of viscous time scales, Comptonization and traversal time along the jet, but detailed modeling is required to confirm this scenario. Another scenario is that the observed delays are simply the light travel times across the disk. Assuming the upper limit of disk size to be the circularization radius of the accretion disk and considering the orbital period (1.54 days for XTE J1550-564), the disk size is calculated to be $\sim$ 106 km and the light travel time is found to be $<$ 4 s. We argue that the observed delays could also be attributed to the light travel times.

In conclusion, we report a dynamical CCF study between soft and hard X-ray energy bands for the black hole source XTE J1550-564, in SPL state. We found complex CCF structures in the total light curve with a dynamical correlation time scale of 50 s. Correlated and anti-correlated delays were observed on the order of $<$ $\pm$ 15 s. It was noticed that these delay time scales are similar to the delays observed in CCFs between X-ray and optical/IR bands. We suggest that similar studies of various other spectral states in both black hole and neutron star sources would be useful for understanding the associated short time scale variations and connected processes in the accretion disk. Upcoming X-ray observatories like *Astrosat* and NHXM, which have better resolution in soft energy bands (i.e.$<$1 keV) will give a vivid picture of the dynamical CCF and would be explicitly useful for the modeling of high cadence variation arising from the accretion disk.

ACKNOWLEDGMENTS

This research has made use of data obtained through the HEASARC Online Service, provided by the NASA/GSFC, in support of NASA High Energy Astro physics Programs. K.S. acknowledge the support from the Young Scientist scheme (Fast Track program) under DST–SERB project, Government of India.

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