Article

Discovery of Jet Induced Soft Lags of XTE J1550-564 during its 1998 Outburst

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Abstract: X-ray time lags are complicated in nature. The exact reasons for complex lag spectra are yet to be known. However, the hard lags, in general are believed to be originated due to inverse Comptonization process. But, the origin of soft lags remained mischievous. Recent studies on “Disk-Jet Connections” revealed that the jets are also contributing in the X-ray spectral and timing properties in a magnitude which was more than what was predicted earlier. In this article, we first show an exact anti-correlation between X-ray time lag and radio flux for XTE J1550-546 during its 1998 outburst. We propose that the soft lags might be generated due to the change in the accretion disk structure along the line of sight during higher jet activity.

Keywords: accretion: accretion disks, Radio Jets and outflows, individual - XTE J1550-564, X-ray time lags

1. Introduction

Accretion onto black holes are one of the most energy efficient process that occurs in our universe. During accretion, matter heats up via losing potential energy and radiates. The radiation can be detected throughout the entire electromagnetic spectrum. The nature of such radiations are found to be varying over timescales ranging from sub-second to few days. In X-ray regime, Quasi Periodic Oscillations or QPOs are found for most of the Galactic Black Holes (hereafter GBHs) by taking FFT of the observed light-curve and can be of different types (see [1]). The centroid frequency (νc) of QPOs which varies between 0.01 − 20 Hz are considered as Low Frequency QPOs. The origin of such QPOs are described by shock oscillation model (see [2]) and also via Lense-Thirring precision model ([3]). Phase/Time lags are computed by taking cross spectrum of two different energy bands of the observed X-ray light curve ([4]). Hard lag of positive lag is found when harder photons delay over the soft/reference band. Soft/negative lag is produced when the hard photons reach the observer prior to the soft photons. Hard lags are most commonly interpreted by the inverse Comptonization [5] while soft lags were modeled by propagatory perturbation model (see [6] and[7]). Also, it was suggested that the hard X-ray which are reprocessed by the Keplerian disk could explain the soft lags found in case of GBHs and AGNs [8]. Recently, the
dependency of lag signs over the inclination angle of the disk was brought into light (see [9] and [10]) where the high inclination GBHs are documented as more prone to exhibit soft lags. However, the connection between X-ray timing properties and radio jets became tighter when origin of type-B QPOs due to the oscillation of the base of the jet was recommended [10].

Jets are one of the common mechanism via which a part of the accreting matter is ejected. In recent years, the studies of apparent superluminal jet launching mechanism (see [11] for details) from the disk has evolved from the point of observations. Earlier, the disk and jets are believed to be of different origin. X-ray flux ($F_X$) and radio flux ($F_R$) correlation for the entire mass range of black holes ([12]; [13], [14]; [15] and [16]) suggested a strong connection between accretion disk and radio jets. Lag between X-ray and optical band of GX-339-4 [17] implicates the lag may have originated due to the modulation of magnetic field near the jet base. These studies raised questions whether the time lag which is calculated by integrating over the $v_c \pm \text{FWHM}$ has any contribution from the jet. In presence of Comptonization, reflection and gravitational bending, complex lag properties of GBHs were examined [18] where it was discussed that the outflows/jets should be a major component which could enhance the formation of soft lags. GRS 1915+105 had followed a pattern where it changed the lag sign during higher radio activity [19].

Keeping this disk-jet connections in mind, we studied XTE J1550-564 which was observed in multi-wavelengths. It was discovered by the All-Sky Monitor (ASM) on board Rossi X-Ray Timing Explorer (RXTE) in 1998 [20]. RXTE spectral observations of XTE J1550-564 was reported [21] and an estimated mass of the black hole was found to be $M_{BH} \sim 10M_\odot$. The source was observed in multi-wavelengths during its 1998 outburst [22]. The outburst begins with a hard X-ray spike, but the soft X-ray originated from the standard disk dominated in the later stages. [23] reported the discovery of strong QPOs from the X-ray light curves of XTE J1550-564. A high frequency QPOs near 160−215 Hz was reported [24]. In the rising state, significant hard lags were seen [25].

In this paper, we investigate radio flux and X-ray time lag of GBH XTE J1550-564. We provide data analysis process and results in the following sections. In §4, we discuss the origin of such correlation under Two Component Advective Flow (see [26]) paradigm and we draw our conclusion in §5.

2. Data analysis

RXTE PCA archival data is used to generate lag spectra. Cross spectra are calculated. Phase lag between two band signals at a Fourier frequency $v_j$ is given by $\phi_j = \text{arg}[CF(j)]$ and the corresponding time lag is $\phi_j/2\pi v_j$ (see [27]). Lags are calculated at the QPO centroid frequency ($v_c$) integrating over the interval $v_c \pm \text{FWHM}$ for 5-13 keV energy band against 2-5 keV energy band.

For XTE 1550-564, we have used the published radio flux at 843 MHz from MOST by [22] and 8.6 GHz from ATCA radio telescope by [30] respectively.

3. Results

During the 1998 outburst, the source was observed in radio, optical and X-rays. The radio and optical counterparts of the source was reported (see for details [28] and [29]). RXTE monitored the X-ray activity which maximized around MJD 51076. Subsequently, a giant radio jet was observed.

The rising state of the outburst continued until MJD 51076. The QPO frequency increased. But, the associated lag changed the sign after MJD 51070. From Fig. 1a, we can see the increase in X-ray soft lags with the increase in radio flux. The correlation curve in Fig. 1b suggest the jet activity induced soft lags for this outburst. The Pearson Correlation Coefficient is $-0.754$ for this outburst. Here, we have reported only up to MJD 51093 as the QPOs after that became sporadic in nature and simultaneous radio observations were absent. Also, X-ray spectral studies of XTE J1550-564 was carried out where
Figure 1. (a) Radio flux and X-ray lags are plotted with MJD for XTE J155-564. (b) Correlation between radio flux and time lag is plotted for XTE J1550-564. We opted for near simultaneous approach for the radio and time lag data. The fitted slope ($a = -6.01 \times 10^{-6}$) is found to be negative.

the absence of QPOs are reported after MJD 51150 and the X-ray spectra was found to be highly disk dominated in the $2-20$ keV range [21].

4. Discussion

QPOs and associated phase or time lags are one of the major information carrier of accretion disk geometry as well as their evolution during outbursts. The QPO centroid frequency ($\nu_c$) directly correlates with size of the Compton cloud (see [2] for further details). On the other hand, lags are associated with fluctuation of thermodynamical parameters like density, temperature, reflection coefficient of the Keplerian disk and interception fraction of the soft photons (see [18] for further details). Recent studies of spectral (see [31], [32] and [33] for further details) and temporal (see [1]) variabilities showed significant spectral hardening and QPO $\nu_c$ and/or rms variation due to inclination angle variation. Later, similar inclination dependency of lag signs were seen (see [9] and [10]). It was shown that the soft lags are mostly found for the GBHs which are at high inclination angle.

XTE J1550-564 had undergone an outburst during 1998 where the X-ray flux has reached 6.8 crab. During this time, the source had also shown a giant radio flare of $\sim 376$ mJy (see [22]). Associated lags also evolve with $\nu_c$ and radio flux. From Fig. 1a, we can see an anti-correlation between time lags and radio flux. The Fig. 1b suggests a strong correlation between radio flux and soft lags.

Under Two Component Advective Flow (TCAF) paradigm (see [26] for further details), we investigate the physical origin of such correlation. The advective flow contains a sub-Keplerian component and a Keplerian disk. Reaching the centrifugal barrier, the flow undergoes a shock which slows down the inflowing matter. This causes a sudden rise of temperature which puffs up the matter creating a hotter region known as CENBOL which is responsible for the inverse Comptonization of the soft photons generated by the Keplerian disk. Using hydrodynamic simulations (see [34] and [35]), one finds self-consistent outflows are being produced from the post-shock region. In our model, the QPOs are
Figure 2. Cartoon diagram of Two Component Advective Flow (TCAF) in presence of Return OutFlow (ROF) is shown. Pseudo colors represent approximated temperature profile within the disk. Six emergent photon types are shown in the cartoon. Photon type (1) denotes the soft photons which have suffered gravitational bending but are not intercepted by the CENBOL. Photon (2) represents the hard photons which are scattered in the CENBOL and undergone gravitational bending to reach the distant observer at high inclination angle. Photon (3) scattered in the CENBOL and without suffering bending reach the observer. The fourth category of photons belong to the hard photons which are reflected by the Keplerian disk. Number five represents the soft photons which arrived the detector plane without scattering. Photon type (6) denotes the photons which scattered in the Compton cloud and again downscattered in the ROF region while reaching the observer.

generated due to the shock oscillation at the CENBOL boundary. During accretion, a fraction of inflowing matter forms outflow. As the spectral state changes from hard to intermediate states, the amount of outflow increases and so does the $v_c$. A part of the outflowing matter which fails to achieve the escape velocity, returns to inflow causing the formation of a region cooler, yet denser than the rest of the inflow. The scattered hard photons passes through this region to reach the observer at high inclination angle. While passing through this Return OutFlow (ROF) region, a fraction of the hard photons downscatter. These downscattered photons (type 4 in Fig. 2) lags behind rest of the hard radiation (type 3 & 3 in Fig. 2) emitted from Compton cloud. We argue that the origin of soft lag could be explained by the downscattering of the hard radiation in the ROF region. Similar correlations for other sources at high inclination angle were found and reported [36].

5. Conclusions

We report a correlation between radio flux and X-ray time lag for XTE J1550-564 during its 1998 outburst from which we can conclude that the soft lags are simultaneous with the radio flux. Our finding provides a model independent insight to the disk-jet connection and implicates the severity of simultaneous broadband studies of astrophysical black holes to be able to acquire deeper understanding.

Author Contributions: A.C simulated the lag variation in presence of outflows and wrote the manuscript. B.D.G and D.P analyzed the data. S.K.C supervised the project and modified the manuscript. P.N provided the correlation data.

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Conflicts of Interest: The authors declare no conflict of interest.
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