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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 as yet unknown. However, the hard lags, in general, are believed to be originated due to inverse Comptonization process. However, 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 anticorrelation 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 disks; radio jets and outflows; individual—XTE J1550-564; X-ray time lags

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1. Introduction

Accretion onto black holes is one of the most energy-efficient processes that occurs in our universe. During accretion, matter heats up by losing potential energy and then 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 the X-ray regime, Quasi Periodic Oscillations (QPOs) are found for most of the Galactic Black Holes (GBHs) by taking FFT of the observed light curve and can be of different types (see the work by the authors of [1]). The centroid frequency (ν_c) of QPOs, which varies between 0.01 and 20 Hz, is considered a Low-Frequency QPOs. The origin of such QPOs are described by the shock oscillation model (see the work by the authors of [2]) and also via the Lense–Thirring precision model [3]. Phase/time lags are computed by taking cross-spectra 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], whereas soft lags were modeled by propagatory perturbation model (see the works by the authors of [6,7]). Also, it was suggested that the hard X-rays, which are reprocessed by the Keplerian disk, could explain the soft lags found in the case of GBHs and AGNs [8]. Recently, the dependency of lag signs over the inclination angle of the disk was brought into light (see the work by the authors of [9,10]) 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, because oscillation at the base of the jet was recommended [10].

Jets are one of the common mechanisms via which a part of the accreting matter is ejected. In recent years, the studies of apparent superluminal jet launching mechanism (see the work by the authors of [11] for details) from the disk has evolved from the point of observations. Earlier, the disk and jets were believed to be of different origin. The X-ray flux (F^X) and radio flux (F^R) correlation for the entire mass range of black holes [12–16] suggested a strong connection between accretion disk and radio jets. Lag between X-ray and the optical band of GX-339-4 [17] implies that the lag may have originated due to the modulation of magnetic field near the jet base. These studies raised questions of whether the time lag, which is calculated by integrating over the $\nu_c \pm FWHM$, 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 the Rossi X-ray Timing Explorer (RXTE) in 1998 [20]. RXTE spectral observations of XTE J1550-564 were 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. The authors of [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 Section 4, we discuss the origin of such correlation under Two-Component Advective Flow (see the work by the authors of [26]) paradigm, and we draw our conclusion in Section 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 ν_j is given by $\phi_j = arg[CF(j)]$ and the corresponding time lag is $\phi_j/2\pi\nu_j$ (see the work by the authors of [27]). Lags are calculated at the QPO centroid frequency (ν_c) integrating over the interval $\nu_c \pm FWHM$ for the 5–13 keV energy band against the 2–5 keV energy band.

For XTE 1550-564, we used the published radio flux at 843 MHz from MOST by the authors of [22] and 8.6 GHz from the ATCA radio telescope by the authors of [28].

3. Results

During the 1998 outburst, the source was observed in radio, optical, and X-rays. The radio and optical counterparts of the source were reported (see for details the work by the authors of [29,30]). 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. However, the associated lag changed the sign after MJD 51070. From Figure 1a, we can see that the X-ray soft lags increase with increasing radio flux. The correlation curve in Figure 1b suggests 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 were carried out where the absence of QPOs was reported after MJD 51150, and the X-ray spectra was found to be highly disk-dominated in the 2 to 20 keV range [21].

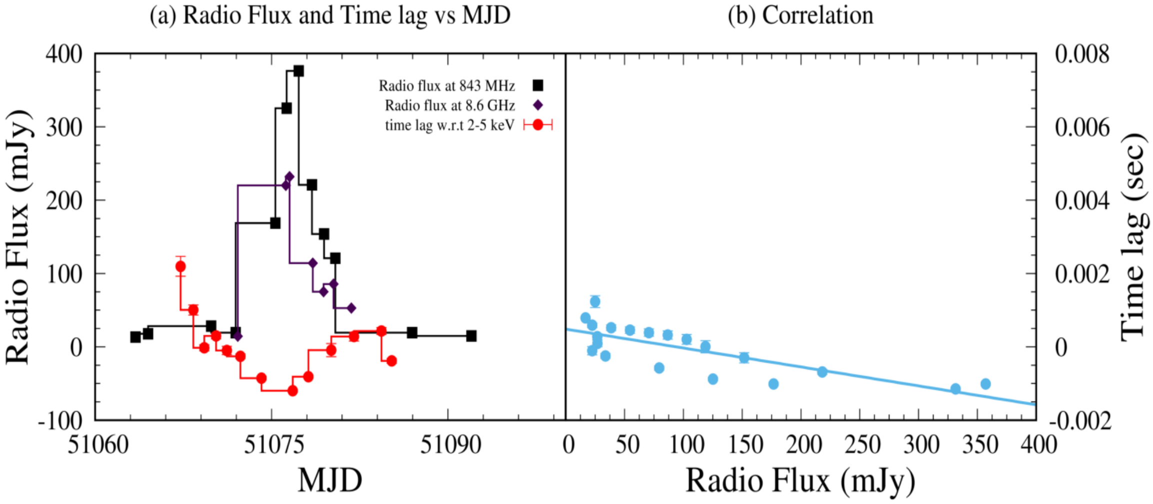

Figure 1. (**a**) Radio flux and X-ray lags are plotted with MJD for XTE J155-564. (**b**) Correlation between radio flux and time lag is plotted for XTE J1550-564. We opted for near simultaneous approach for the radio and time lag data. The fitted slope ($a = -6.01 \times 10^{-6}$) is found to be negative.

4. Discussion

QPOs and their associated phase or time lags are major information carriers of accretion disk geometry as well as their evolution during outbursts. The QPO centroid frequency (ν_c) directly correlates with the size of the Compton cloud (see the work by the authors of [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 the work by the authors of [18] for further details). Recent studies of spectral (see the works by the authors of [31–33] for further details) and temporal (see the work by the authors of [1]) variabilities showed significant spectral hardening and QPO ν_c and/or *rms* variation due to inclination angle variation. Later, similar inclination dependency of lag signs were seen (see the works by the authors of [9,10]). It was shown that the soft lags are mostly found for the GBHs at high inclination angles.

XTE J1550-564 had undergone an outburst during 1998 where the X-ray flux reached 6.8 crab. During this time, the source had also shown a giant radio flare of ~376 mJy (see the work by the authors of [22]). Associated lags also evolve with ν_c and radio flux. From Figure 1a, we can see an anticorrelation between time lags and radio flux. Figure 1b suggests a strong correlation between radio flux and soft lags.

Under the Two-Component Advective Flow (TCAF) paradigm (see the work by the authors of [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 the work by the authors of [34,35]), one finds that self-consistent outflows are being produced from the post-shock region. In our model, the QPOs are 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 ν_c. A part of the outflowing matter that 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 Figure 2) lags behind rest of the hard radiation (type 3 & 3 in Figure 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].

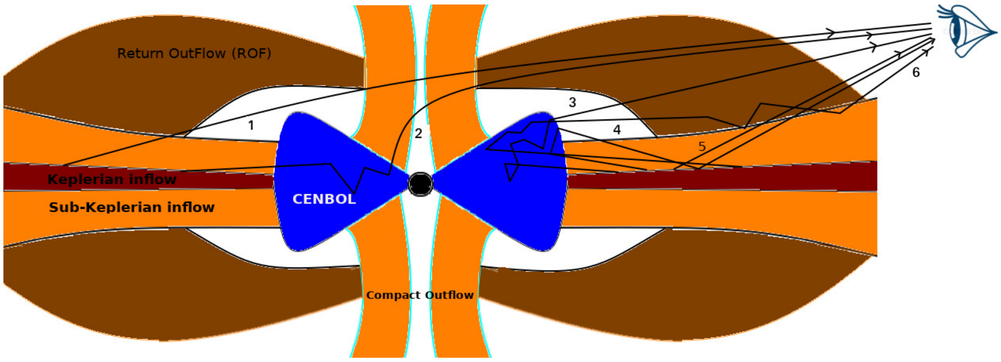

Figure 2. Cartoon diagram of two-component advective flow (TCAF) in the presence of Return OutFlow (ROF) is shown. Pseudo-colors represent approximated temperature profile within the disk. Six emergent photon types are shown in the cartoon. Photon type 1 denotes the soft photons which have suffered gravitational 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 type 3 is scattered in the CENBOL without suffering bending reaching the observer. The fourth category of photons is the hard photons, which are reflected by the Keplerian disk. Number five represents the soft photons that arrive the detector plane without scattering. Photon type (6) denotes the photons that are scattered in the Compton cloud and again downscattered in the ROF region while reaching the observer.

5. Conclusions

We report a correlation between the 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.G.D. 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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