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Phase lag and quasi-periodic oscillation frequency correlation in galactic black hole candidate XTE J1550-564

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Abstract. The complex behavior of Fourier phase lags associated to Quasi-Periodic Oscillations (QPOs) is one of the most significant observational effects of Galactic black hole sources. This temporal property can diagnoses the dynamics of accretion flow around the black holes. We analyze RXTE/PCA data of the black hole source XTE J1550-564 for the 1998 outburst. We find smooth decrease of the time lag(s) with time in the rising phase and in the declining phase, its increases with time. We conclude that this variation could be due to the movement of the comptonizing region itself. We also find that evolution of phase/time lag is correlated with the QPO frequency. This behavior suggests towards a common evolution scenario of the black hole transient XTE J1550-564 through its outburst.

Keywords : stars: individual: XTE J1550-564 – methods: data analysis – black hole physics – radiation mechanisms: general

1. Introduction

Studying the temporal X-ray properties such as Fourier frequency dependent phase lag and coherence function of X-ray emission is important to diagnose the dynamics of accretion flows around black hole candidates. The Galactic black hole candidate XTE J1550-564 is one of the best studied soft X-ray transient over a wide range of wavelengths. The complex outburst profile of XTE J1550-564 during 1998 begins and ends in the low/hard state, which is quite common in other outburst candidate of black holes (e.g., GRO J1655-40, GX 339-4).This nature of outburst behavior is understood to be caused by sudden variation of viscosity in the system (Mandal & Chakrabarti, 2010). The phase lag evolved during the initial rising phase of 1998 outburst (Cui et al. 1999, 2000) and its magnitude increases with X-ray flux. The coherence function is high and roughly constant up to the first harmonic of the QPO. It is observed that

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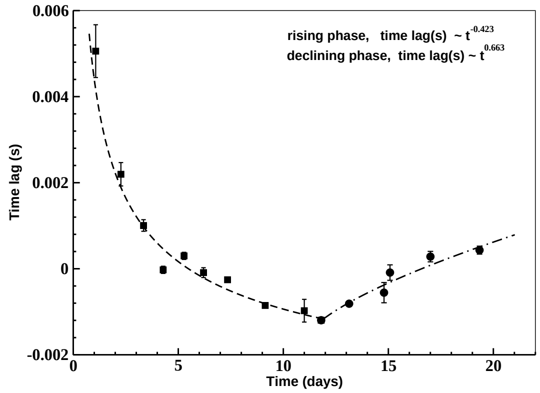

Figure 1. Time lag at QPO centroid frequency (f_Q) integrated over the width equal to FWHM (F_w) of the QPO itself is plotted as a function of number of days during rising (MJD 51065 to MJD 51076) and declining (MJD 51076 to MJD 51084) phases of the 1998 outburst.

the coherence function increases at the QPO frequency and its harmonics (Cui et al. 2000). It also found that the QPO becomes stronger at higher energies (Cui et al.1999) which directly supports the view that QPO may originates due the modulated photons count from comptonizing region.

2. Observations

The data used in this analysis was taken from *RXTE* public archive. We produced a phase lag spectrum for each observation where QPO exists. We divide the PCA data into two energy bands soft (2-5 keV) and hard (5-13 keV). We calculate a cross spectrum for every 16 s (see Reig et al. 2000). We calculate averaged cross-spectrum vectors for each observation, from which we derived phase lag spectra. Positive phase lag indicates that the hard photons (5-13 keV) lags behind the soft photons (2-5 keV). We calculate the phase lag at on the QPO centroid frequency (f_Q) with a width equal to FWHM (F_w) of the QPO itself (see Reig et al. 2000).

3. Discussion

Fig. 1 shows the systematic variation of the frequency dependent time lag(s) as a function of day during the rising (MJD 51076 to MJD 51084) and declining (MJD 51076 to MJD 51084) phases of the outburst. We term the 0^{th} day when the first QPO was observed (i.e., MJD 51065). The observation is covering the first three weeks of the outburst. We fitted the time lag(s) variation in the rising phase with a curve, where time lag(s) $\sim t^{-0.423}$ and reduced χ^2 close to 1.3. We clearly observe that as time progresses (also QPO frequency increases) time lag(s) decreases during the rising phase and we also find a systematic variation of frequency dependent time

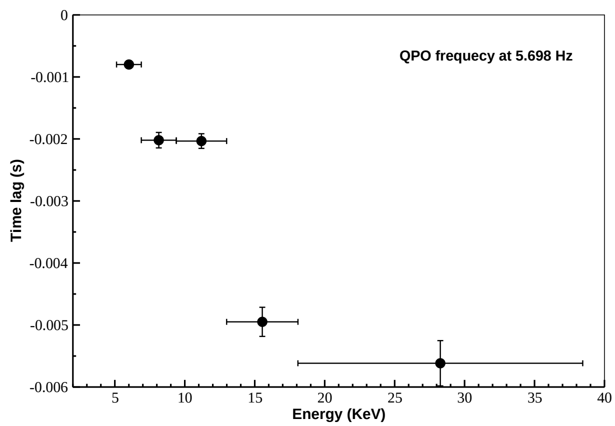

Figure 2. Energy dependence of time lag(s) for at QPO centroid frequency ($f_Q = 5.698 Hz$) is plotted. The time lag(s) is integrated over the width equal to FWHM (F_w) of the QPO itself. Here we choose 1.94-5.14 KeV as a reference energy band. The other energy bands are 5.12-6.89 KeV, 6.89-9.39 KeV, 9.39-12.99 KeV, 12.99-18.09 KeV and 18.09-38.44 KeV.

lag(s) with time during the declining phase. The declining phases starts after the highest value of $\nu_{QPO} = 13.1$Hz was observed (i.e., MJD 51076). The fitted curve represents time lag(s) $\sim t^{0.663}$ with a reduced χ^2 close to 1.6. Fig. 2 shows that the Fourier frequency dependent time lags(s) at a QPO frequency 5.698 Hz exhibit a logarithmic energy dependence.The hard photons lags behind the soft photon as the hard photons undergo several scattering before the emission from that region. We find higher Fourier frequencies show shorter time delays. The photons taking part in the higher frequency variability should have scattered over short distances (as QPO frequency increases shock location decreases which in turn decreases the size of the Comptonizing region) and thus will show relatively short time delays between soft and hard photons.

Fig. 3 represents a correlation between phase/time lag(s) and QPO frequency for both the rising and declining phases of the outburst. We find a perfect linear correlation between them for both phases. This behavior indicates that both the QPOs (during rising and reclining phases) may originate from the same oscillation process (Chakrabarti et al. 2005, 2008 & 2009). It is evident (Dutta & Chakrabati 2010, Chakrabarti et al. 2009) that in the rising phase, a systematic variation of QPOs are due to slow drifting of the oscillating shocks towards the black hole. But in the decline phase, the oscillating shock propagates outwards.

4. Conclusion

The physical picture during the initial days of the 1998 outburst becomes clearer after studying the time lag(s) variations with time. In the rising phase, the excess cooling in

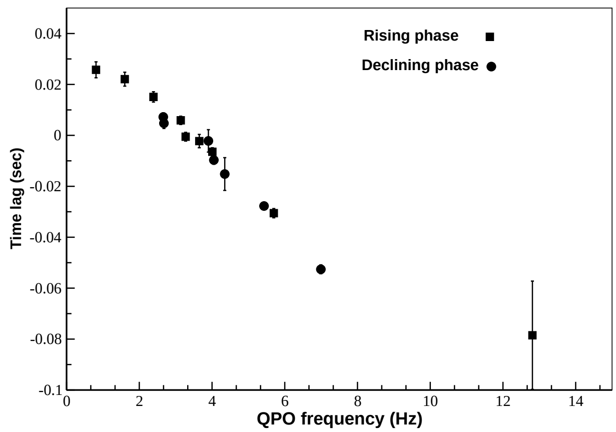

Figure 3. The correlation between QPO frequency (Hz) and corresponding phase lag (rad) at the QPO frequency. The correlation suggests towards a common evolution scenario of black hole transients XTE J1550-564 during its outburst.

the post-shock flow (which is the CENtrifugal pressure supported BOundary Layer or CENBOL; Chakrabarti & Titarchuk 1995) causes a steady drift of the shock towards the black hole and in the declining phase the recession of the Keplerian disc causes the reduction of pressure in the pre-shock flow and the shock can propagate outward. Thus, the smooth decrease of the time lag(s) with time is due to the movement of the Comptonizing region itself which in turn reduces its geometrical size with time (as QPO frequency increases). Again, in the declining phase this movement in the opposite direction increases its size as a result time lag(s) increases with time.

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