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PHASE LAG AND COHERENCE FUNCTION OF X-RAY EMISSION FROM BLACK HOLE CANDIDATE XTE J1550−564

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ABSTRACT

We report the results from measuring the phase lag and coherence function of X-ray emission from black hole candidate XTE J1550−564. These temporal X-ray properties have been recognized to be increasingly important in providing important diagnostics of the dynamics of accretion flows around black holes. For XTE J1550−564, we found significant hard lag—the X-ray variability in high-energy bands *lags* behind that in low-energy bands—associated both with broadband variability and quasi-periodic oscillation (QPO). However, the situation is more complicated for the QPO: while hard lag was measured for the first harmonic of the signal, the fundamental component showed significant *soft* lag. Such behavior is remarkably similar to what was observed of microquasar GRS 1915+105. The phase lag evolved during the initial rising phase of the 1998 outburst. The magnitude of both the soft and hard lags of the QPO increases with X-ray flux, while the Fourier spectrum of the broadband lag varies significantly in shape. The coherence function is relatively high and roughly constant at low frequencies and begins to drop almost right after the first harmonic of the QPO. It is near unity at the beginning and decreases rapidly during the rising phase. Also observed is that the more widely separated the two energy bands are, the less the coherence function between the two. It is interesting that the coherence function increases significantly at the frequencies of the QPO and its harmonics. We discuss the implications of the results on the models proposed for black hole candidates.

Subject headings: black hole physics — stars: individual (XTE J1550−564) — stars: oscillations — X-rays: stars

1. INTRODUCTION

Black hole candidates (BHCs) are characterized by rapid X-ray variability (see recent reviews by van der Klis 1995 and Cui 1999a). It is also common for BHCs that the variability at high energies lags behind that at low energies (Cui 1999a and references therein), which is often referred to as hard lag. The hard lag is often attributed to thermal inverse Comptonization processes (e.g., Miyatomo et al. 1988; Hua & Titarchuk 1996; Kazanas, Hua, & Titarchuk 1997; Böttcher & Liang 1998; Hua, Kazanas, & Cui 1999), which are generally thought to be responsible for producing the characteristic hard tail in the X-ray spectra of BHCs (Tanaka & Lewin 1995). In these models, the hard lag arises simply because a greater number of scatterings are required for seed photons to reach higher energies. Therefore, the lag is directly related to the diffusion timescale through the Comptonizing region, which scales logarithmically with photon energy (e.g., Payne 1980; Hua & Titarchuk 1996). The expected logarithmic energy dependence of the hard lag is in rough agreement with the observations (Cui et al. 1997; Crary et al. 1998; Nowak et al. 1999). However, the measured lag is often large (e.g., a few tenths of a second) at low frequencies, which would require a very extended Comptonizing region (Kazanas et al. 1997; Böttcher & Liang 1998; Hua et al. 1999). It is not clear whether such a region can be physically maintained (Nowak et al. 1999; Böttcher & Liang 1999; Poutanen & Fabian 1999). Suggestions have also be made to link the hard lag either to the propagation or drift timescale of waves or blobs of matter through an increasingly hotter region toward the central black hole where hard X-rays are emitted (Miyamoto et al. 1988; Kato 1989; Böttcher & Liang 1999) or to the evolution timescale of magnetic flares (Poutanen & Fabian 1999). Regardless of which scenario turns out to be close to reality, it is clear that the hard lag is an important property of BHCs which we can use to gain insight into the geometry and dynamics of accretion flows in these systems.

Recently, however, it was discovered that a strong quasi-periodic oscillation (QPO) in GRS 1915+105, a well-known microquasar, had a rather complex pattern of phase lag (Cui 1999b): while the hard lag was measured for the odd harmonics of the signal, the even harmonics displayed *soft* lag. The pattern is puzzling because it does not fit naturally into any of the models suggested for BHCs. Speculation was made that the complicated QPO lag in this case might be caused by a change in the form of the wave that produced the QPO (Cui 1999b). It is, however, not clear what physical mechanisms could be responsible for such evolution of the wave form. Similar behavior was subsequently observed for some of the QPOs in XTE J1550−564 (Wijnands, Homan, & van der Klis 1999). Therefore, the phenomenon may actually be common for BHCs.

A related timing property to the phase lag is the coherence function between two different energy bands. Only recently, however, has enough attention been paid to the importance of this property (Vaughan & Nowak 1997) and have efforts been made to compute it along with the phase lag. Consequently, the results are very limited. It is nevertheless interesting to note that for BHCs the coherence function often appears to be around unity over a wide frequency range—the X-ray variabilities in different energy bands are almost perfectly linearly correlated on those timescales in the Fourier domain (Vaughan & Nowak 1997; Cui et al. 1997; Nowak et al. 1999). This puts additional constraints on the models for X-ray produc-

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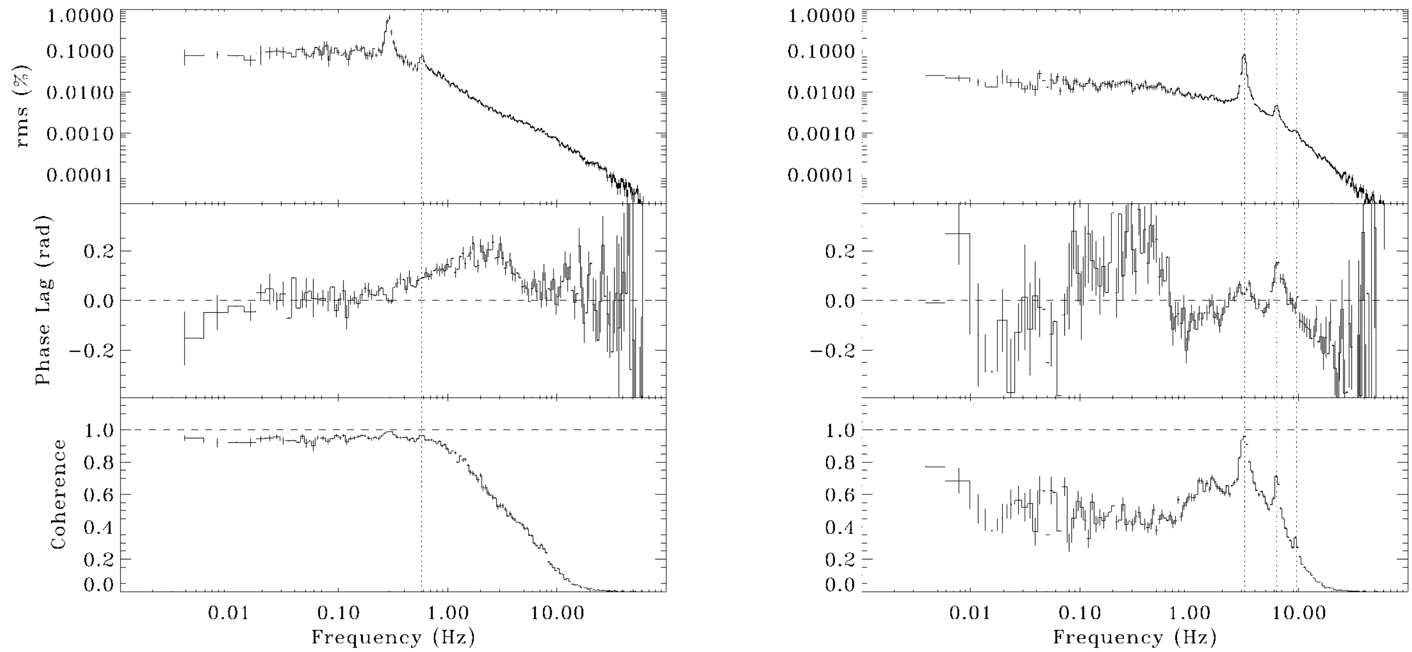

FIG. 1.—Sample Fourier spectra of power density, phase lag, and coherence function. The left panels show the results derived from observation 3 (following Paper 1), and the right panels the results from observation 10. Note the difference in the shape of the broadband phase lag spectrum between the two cases. The dotted lines indicate the frequencies of the QPO and its harmonics.

tion mechanisms in BHCs. Lower coherence was observed of Cyg X-1 when the source was in the transitional periods between the two spectral states (Cui et al. 1997). This could be attributed to the variation of the Comptonizing region during those episodes on timescales less than an hour (Cui et al. 1997) in the context of Comptonization models (Hua, Kazanas, & Titarchuk 1997). However, more data is required to verify such a scenario.

In this Letter, we present the results from measuring the phase lag and coherence function of X-ray variability for XTE J1550−564 during the initial rising phase of the 1998 outburst (Cui et al. 1999, hereafter Paper 1). In addition to the intense aperiodic variability, a strong QPO was detected along with its first and sometimes second harmonics, and the frequency of the QPO increased by almost 2 orders of magnitude during this period (Paper 1). We examine the timing properties of both the QPO and broadband variability.

2. DATA AND ANALYSES

Paper 1 should be consulted for the details of the observations. Very briefly, there were 14 *Rossi X-Ray Timing Explorer* observations covering the rising phase of the outburst. In the first observation, however, the overflow of the on-board data buffers (owing to the inappropriate data modes adopted) produced gaps in the data. For this work, we chose to ignore this observation entirely. For the remaining 13 observations, we rebinned the data with 2^{-7} s time bins and combined the *event* and *binned* data into the six energy bands as defined in Paper 1.

We chose the 2–4.5 keV band as the reference band. A cross power spectrum (CPS) was computed for each 256 s data segment between the reference band and each of the higher energy bands. The results from all segments were then properly weighed and averaged to obtain the CPSs for the observation. The phase of a CPS represents a phase shift of the light curve in a selected energy band with respect to that of the reference band. We followed the convention that a positive phase indicates that the X-ray variability in the high-energy band lags behind that in the low-energy band, i.e., a hard lag. The uncertainty of the phase lag was estimated from the standard deviations of the real and imaginary parts of the CPS. For the phase lag associated with a QPO, the magnitude was derived from fitting the CPS in a narrow frequency range around the QPO with a linear function (for the continuum) and two Lorentzian functions, whose centroid frequencies and widths were fixed at those of the QPO (Paper 1). Acceptable fits (i.e., the reduced χ^2 around unity) were obtained for all cases. The corresponding errors were derived by varying the parameters until $\Delta\chi^2 = 1$ (i.e., representing roughly 1 σ confidence intervals; Lampton, Margon, & Bowyer 1976).

3. RESULTS

In all observations, significant hard lag was found to be associated with the broadband variability. The phase lag shows significant evolution during the rising phase, which can be divided into two distinct periods. Figure 1 shows an example for each period of Fourier spectra of power density, phase lag, and coherence function. At the early stage of the rising phase, the broadband hard lag is significantly measured only in the middle range of frequencies. The lag increases with frequency first, peaks at some characteristic frequency, and then decreases. The peak frequency does not appear to correspond to any characteristic features in the power density spectrum. At the frequency of the QPO, *soft* lag is clearly detected on top of the broadband hard lag. However, there does not appear to be significant phase lag (hard or soft) associated with the first harmonic. At the later stage of the rising phase, while the hard lag is still apparent, there also seems to be significant *soft lag* associated with the broadband variability at frequencies around the QPO and its harmonics. The soft lag associated with the fundamental component of the QPO remains significant, but now *hard* lag is also measured for the first harmonic. As for

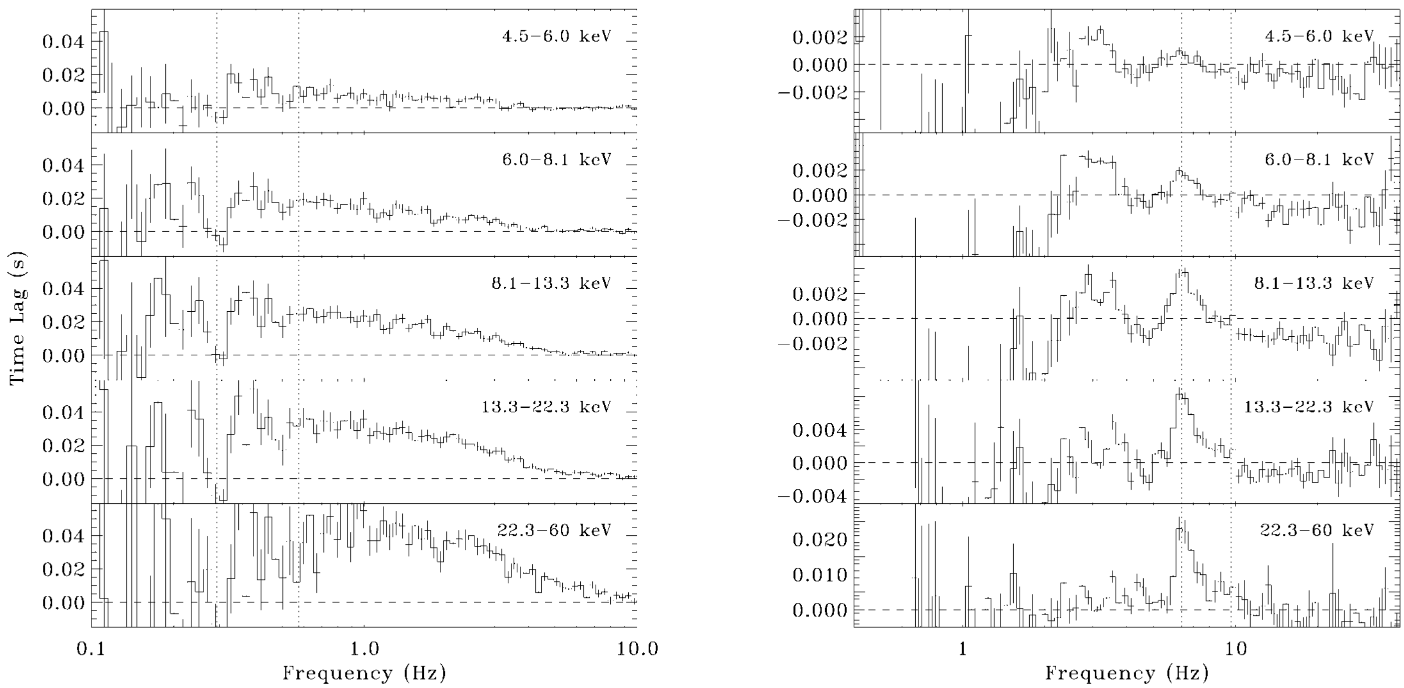

FIG. 2.—Energy dependence of time lag. As for Fig. 1, the results for observations 3 and 10 are shown for illustrative purposes. The dotted lines indicate the frequencies of the QPO and its harmonics.

the coherence function, it is high and nearly constant at low frequencies and drops off sharply almost right after the first harmonic of the QPO for both periods of the rising phase. It is interesting to notice that at the frequencies of the QPO and its harmonics, the coherence function increases significantly.

Both the broadband and QPO lags show strong energy dependence, as illustrated in Figure 2. They become larger at higher energies (with respect to the reference band), which is typical of BHCs (Cui 1999a). The QPO lag also shows correlation with X-ray flux (and thus with the QPO frequencies; Paper 1) for the second period of the rising phase, as is apparent in Figure 3. Both the soft and hard QPO lags increase as the source brightens, reaching as high as 0.1 and 0.3 radians, respectively. The coherence function is near unity at the beginning of the rising phase. Subsequently, it decreases rapidly and seems to level off in the end. To quantify the evolution, we averaged the observed values over a frequency range 0.004–0.1 Hz where the coherence function is roughly constant. As an example, the results for the 8.1–13.3 keV band are plotted in Figure 4. The loss of coherence is apparent during the initial rising phase. Moreover, the coherence function also decreases as the separation between the two energy bands widens, as shown in Figure 5.

4. DISCUSSION

Although the broadband hard lag is significantly detected only at intermediate frequencies, large uncertainties prevent us from drawing any definitive conclusions on the results at low

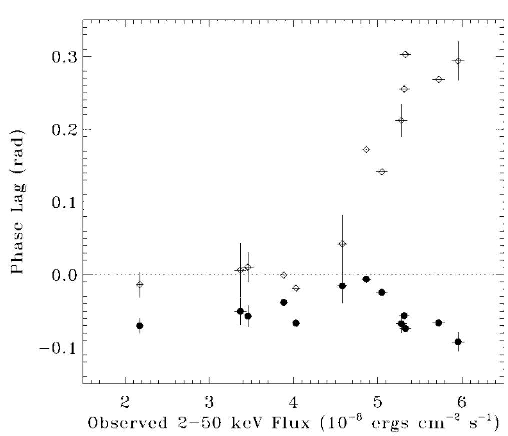

FIG. 3.—Evolution of QPO phase lag with X-ray flux. Filled circles show the measured (soft) phase lag associated with the fundamental component, while the open circles the lag with the first harmonic. Note that starting at the second period of the rising phase (i.e., observation 8) both the soft and hard lags increase markedly with flux.

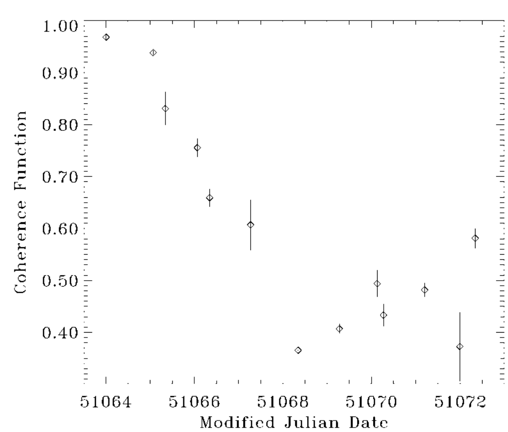

FIG. 4.—Evolution of coherence function during the 1998 outburst. The results shown are for the 8.1–13.3 keV band (with respect to the reference band; see text). They were derived by averaging over 0.004–0.1 Hz, where the coherence function is roughly constant.

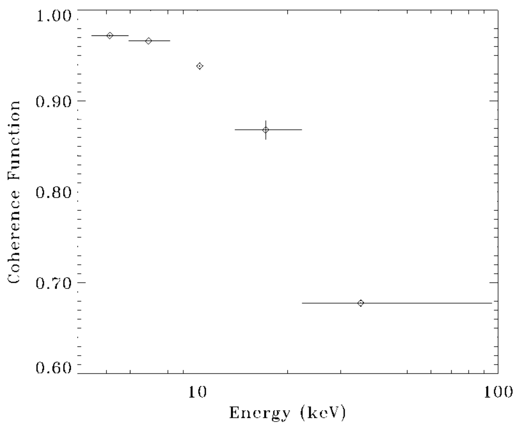

FIG. 5.—Energy dependence of coherence function. The results from observation 3 are shown, as an example. As for Fig. 4, the results are for the 8.1–13.3 keV band and derived by averaging over 0.004–0.1 Hz.

frequencies (where the lag is expected to be small). It appears, from Figure 2, that at the early stage of the rising phase the corresponding *time lag* ($t_{\rm lag} \equiv p_{\rm lag}/2\pi f$) saturates below a characteristic frequency at which the *phase lag* peaks. This is unusual because for other BHCs the time lag seems to monotonically increase toward low frequencies (e.g., Miyatomo et al. 1988; Cui et al. 1997; Grove et al. 1998; Nowak et al. 1999). In the context of Comptonization models, such a saturation in time lag might be the manifestation of the finiteness of the Comptonizing region (Hua et al. 1999). If so, the characteristic frequency (a few hertz) would provide a direct measure of the outer radius of the region (i.e., tens of milli–light-seconds), which seems to be in rough agreement with that estimated from the measured time lag. It is interesting to notice that the characteristic frequency appears to increase as the source brightens, perhaps indicating that the size of the Comptonizing region decreases, as was suggested for Cyg X-1 when the source goes from the hard (or low) state to the soft (or high) state. However, it is puzzling why the lag spectrum appears so different at the later stage of the rising phase, or more specifically what causes the observed broadband *soft* lag around the QPO and its harmonic (see Fig. 1).

The complex pattern of the phase lag associated with the QPO bear remarkable resemblance to that observed of GRS 1915+105 (Cui 1999b). Perhaps the phenomenon is common for certain types of QPOs in BHCs. Combined with the published results (Wijnands et al. 1999), our results show that the phenomenon seems generic for XTE J1550−564, as opposed to being limited to certain spectral states. More importantly, we are now seeing the evolution of the phenomenon as the QPO evolves during the rising phase of the outburst. If we accept the Comptonization scenario for the broadband lag, we would have to rule out this scenario for the QPO because the QPO time lag *increases* with X-ray flux during the rising phase (see Fig. 3). This would not be surprising, since, as discussed by Cui (1999b), it is problematic to attribute the observed soft and hard lags of the QPO (and its harmonic) entirely to inverse Comptonization processes in the first place. At present, no models can naturally account for this type of phase lag phenomenon.

In the context of Comptonization models, the loss of coherence during the rising phase may be due to the variation in the physical conditions of the Comptonizing region (Hua et al. 1997), as was suggested for Cyg X-1 during spectral state transitions (Cui et al. 1997). This scenario might also explain why more widely separated energy bands are less coherent (see Fig. 5), since the difference in the number of scatterings that seed photons experience is greater. The observed Fourier spectra of the coherence function are, however, somewhat unusual. For a number of BHCs, the coherence function is typically close to unity over the entire frequency range where it can be reliably determined (e.g., Vaughan & Nowak 1997; Cui et al. 1997; Nowak et al. 1999). Here, the coherence function drops precipitously above a "break frequency" (which appears to be near the first harmonic of the QPO; see Fig. 1). We speculate that the break frequency might be indicative of the timescale on which the Comptonizing region varies. The break frequency appears to evolve in unison with the frequency of the QPO, which could imply that (1) the QPO originates in the Comptonizing region (instead of the accretion disk, as often thought) and (2) the Comptonizing region varies on an increasingly short timescale during the initial rising phase of the outburst. The former is also supported by the fact that the QPO becomes stronger at higher energies (Paper 1; also see discussion in Cui 1999b). For BHCs in general, such energy dependence of QPOs is observed in most cases (Cui 1999a). Associating the QPO with the Comptonizing region directly might also account for the intriguing increase of the coherence function at the frequencies of the QPO and its harmonics, if the QPO is more localized, given that the broadband variability is probably a disk phenomenon and Compton upscattering of disk photons in an extended nonstatic "corona" can cause the loss of coherence.

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