ALTERNATING LAGS OF QPO HARMONICS: A GENERIC MODEL AND ITS APPLICATION TO THE 67 mHz QPO OF GRS 1915+105

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ABSTRACT

A generic model for alternating lags in quasi-periodic oscillation (QPO) harmonics is presented where variations in the photon spectrum are caused by oscillations in two parameters that characterize the spectrum. It is further assumed that variations in one of the parameters are linearly driven by variations in the other after a time delay \( t_d \). It is shown that alternating lags will be observed for a range of \( t_d \) values. A phenomenological model based on this generic one is developed that can explain the amplitude and phase lag variation with energy of the fundamental and the next three harmonics of the 67 mHz QPO observed in GRS 1915+105. The phenomenological model also predicts the variation of the Bicoherence phase with energy, which can be checked by further analysis of the observational data.

Key words: accretion, accretion disks – black hole physics – stars: individual (GRS 1915+105)

Online-only material: color figures

1. INTRODUCTION

Quasi-periodic oscillations (QPOs) have been observed in both black hole and neutron star systems. For black hole systems, QPO have been observed for a wide range of frequencies from mHz to a few hundred Hz (McClintock & Remillard \textsuperscript{2006}; Remillard \& McClintock \textsuperscript{2006}; van der Klis \textsuperscript{2006}), while kHz QPO have also been observed in neutron star systems (van der Klis \textsuperscript{2006}). The high frequency of these oscillations suggests that they probably originate in the innermost regions of these systems and therefore, in principle, could be used to probe and test effects of general relativity in the strong field limit. Since some of the low-frequency QPO are observed to be correlated with the high-frequency ones, they may have a common origin. Moreover, a study of the temporal behavior of these systems (particularly QPO activity) could give new insight into the enigmatic nature of these systems.

Theoretical studies of the QPO phenomena have generally been restricted to identifying the different frequencies as natural characteristic frequencies of the system and correlations between them (e.g., Miller et al. \textsuperscript{1998}; Stella \& Vietri \textsuperscript{1999}; Titarchuk \& Osherovich \textsuperscript{1999}). A consistent model incorporating radiative and dynamic mechanisms that translates the natural frequency of the system to an observable QPO remains elusive. Clues to such underlying processes can be obtained by studying the energy dependence of the QPO features like amplitude and phase lags (e.g., Cui \textsuperscript{1999}; Lee et al. \textsuperscript{2001}; Li et al. \textsuperscript{2013}; Lin et al. \textsuperscript{2000}; Morgan et al. \textsuperscript{1997}; Qu et al. \textsuperscript{2010}; Reig et al. \textsuperscript{2000}; Rodriguez et al. \textsuperscript{2002}), especially when harmonics are observed since additional information can be obtained for the same phenomenon. Such an endeavor has been impeded because the energy dependence of the phase lags for many QPO are observed to be complex and contrary to expectations (Cui et al. \textsuperscript{2000}; Remillard et al. \textsuperscript{2002}). For example, soft photons are often observed to lag behind high energy photons (Cui \textsuperscript{1999}; Vaughan et al. \textsuperscript{1998}), which is contrary to simple Comptonization models, although recent studies have shown that under certain conditions a soft lag could arise when more than one physical parameter is oscillating (Lee et al. \textsuperscript{2001}). Furthermore, the time lags for low-frequency QPO, \(<1\) Hz, are often large, \(>0.1\) s (Cui \textsuperscript{1999}), and therefore are probably not due to any radiative process and may be due to non-linear multiplicative reverberation effects (Shaposhnikov \textsuperscript{2012}). Large time lags have also been observed for low-frequency non-periodic continuum fluctuations (Nowak et al. \textsuperscript{1999}), which are probably associated with the slow propagation of waves in an accretion disc (Nowak et al. \textsuperscript{1999}; Misra \textsuperscript{2000}) or correspond to the rise/decay time of magnetic flares (Poutanen \& Fabian \textsuperscript{1999}).

Perhaps the most unexpected results are that for some QPO, the phase lag for the odd and even harmonics have opposite signs. Such alternating lag behavior has been observed at different frequencies, e.g., \(67\) mHz (Cui \textsuperscript{1999}) and \(\approx3\) Hz (Lin et al. \textsuperscript{2000}; Reig et al. \textsuperscript{2000}; Tomsick \& Kaaret \textsuperscript{2001}) for GRS 1915+105 and at \(\approx3\) Hz for XTE J1550-564 (Cui et al. \textsuperscript{2000}; Wijnands et al. \textsuperscript{1999}). Possible explanations for such a phenomenon include partial covering models (Varni`ere \textsuperscript{2005}) or radiative transport of photons through a hot Comptonizing medium (Böttcher \& Liang \textsuperscript{2000}). In their model, Ingram et al. (\textsuperscript{2009}) proposed that QPO arises due to the Lense–Thirring precession of the hot inner flow. Based on this, Axelsson et al. (\textsuperscript{2013}) explained the average spectrum and those of a QPO and its harmonic for XTE J1550-564, however, it is not clear whether it can also explain the complex time-lag as function of energy. Axelsson et al. (\textsuperscript{2013}) quote a recent work by Veledina et al. (\textsuperscript{2013}) where they have shown that the existence of a strong harmonic is predicted by the angular radiation pattern from Comptonization of a precessing hot inner flow. Böttcher \& Liang (\textsuperscript{2000}) show that alternating lags for the \(\approx3\) Hz can be explained by time delays due to Comptonization, but such a model is not applicable for the lower-frequency QPO. Since alternating time lags for different harmonics have been observed for different frequencies and for different systems, any model for the phenomenon has to be sufficiently generic and should not depend on the details of QPO production and/or radiative mechanism.

In this work, such a generic model is presented. It is shown that alternating lags will occur under fairly general conditions if the QPO is due to the oscillation of two dependent physical parameters. The two parameters could characterize a single component of the spectrum or could correspond to...
two different spectral components. Based on this interpretative framework, a phenomenological model is developed that can explain the complex energy-dependent features of the 67 mHz QPO observed in GRS 1915+105. In particular, the amplitude and phase lags with energy for the fundamental and the next three harmonics (a total of eight curves) is explained with this model consisting of six parameters. Predictions are made for the energy dependence of the phases of the Bicoherence function, which, in principle, can be checked with further analysis of the observational data.

2. GENERIC MODEL FOR ALTERNATING LAGS

Consider a photon spectrum, \( s(E) \), characterized by two physical parameters, \( a \) and \( b \), such that the temporal variations in the spectrum, \( s(E, t) \rightarrow s_0(E) + \Delta s(E, t) \), are due to corresponding variations in \( a(t) = a_0 + \Delta a(t) \) and \( b(t) = b_0 + \Delta b(t) \). If the response of the spectrum to the variations in the parameters is linear, then

\[
\Delta s(E, t) = \gamma_a(E) \Delta a(t) + \gamma_b(E) \Delta b(t),
\]

where \( \gamma_a \) and \( \gamma_b \) are time-independent functions of energy. In the above equation, it has been assumed that the radiative process time scale (\( \approx t L/c \approx 2 \) ms, where \( \tau \approx 1 \) is the optical depth and \( L \approx 50 G M \left( c^2 \approx 7 \times 10^5 \text{ cm} \right) \) is the size of the system for a ten-solar-mass black hole) is much shorter than the variability time scale of the parameters. In other words, the time lag between the parameter variations and the spectral response is negligible.

In this scenario, the variations in the spectral parameters (\( \Delta a(t) \) and \( \Delta b(t) \)) are caused by a driving dynamical oscillation that produces the QPO. It is further assumed that the variations in \( b \) are also driven linearly by variations in \( a \) after a time lag \( t_d \), that is,

\[
\Delta b(t) = F \Delta a(t - t_d) + D(t),
\]

where \( F \) is a time-independent constant and \( D(t) \) denotes the direct coupling between the driving oscillation and \( b \).

Although the direct coupling term \( (D(t)) \) may not be negligible compared to the interactive term \( F \Delta a(t - t_d) \) for some systems (e.g., Section 3 below), it is convenient to neglect \( D(t) \) at this stage, only to illustrate how such a model could produce alternating lags. With this assumption, a simple equation for the phase lags can be written that explains the origin of the alternating lag behavior in a straightforward manner. Neglecting \( D(t) \) and combining Equations (1) and (2) gives

\[
\Delta S(E, \omega) = \gamma_a(E) \Delta A(\omega)[1 + \gamma_b(E)e^{-i\omega t_d}],
\]

where \( S(E, \omega) \) and \( A(\omega) \) are the Fourier transforms of \( s(E, t) \) and \( a(t) \), respectively, \( \omega \) is the angular frequency and \( \gamma(\omega) \equiv F \gamma_b(E)/\gamma_0(E) \). The cross-spectrum \( C(\omega, E_1, E_2) \) for two energies, \( E_1 \) and \( E_2 \), is defined as \( \Delta S^*(E_1, \omega) \Delta S(E_2, \omega) \).

\[
C(\omega, E_1, E_2) = \gamma_a(E_1) \gamma_b(E_2) [\Delta A(\omega)]^2 \times \frac{[1 + \gamma_b(E_1)e^{i\omega t_d}][1 + \gamma_b(E_2)e^{-i\omega t_d}]}{[1 + \gamma_0(E_1)e^{i\omega t_d}][1 + \gamma_0(E_2)e^{-i\omega t_d}]}. \tag{4}
\]

The phase, \( \phi(\omega, E_1, E_2) \), of the cross-spectrum divided by \( \omega \) is generally identified as the time lag between the photons of energy \( E_1 \) and \( E_2 \). From the form of Equation (4), it can be seen that this phase can be written as

\[
\sin \phi = \frac{m|C|}{|C|} = \frac{(\gamma_0(E_1) - \gamma_0(E_2))\sin(m\omega_0 t_d)}{|1 + \gamma_0(E_1)e^{i\omega t_d}||1 + \gamma_0(E_2)e^{-i\omega t_d}|}. \tag{5}
\]

Here \( \omega \) has been replaced by \( m \omega_0 \), where \( \omega_0 \) is the angular frequency of the fundamental oscillation (first harmonic) and different values of the integer \( m \) correspond to the other harmonics of the system. Since the denominator of Equation (5) is always positive, the sign of the phase angle is determined by \( \gamma(\omega_1) - \gamma(\omega_2) \). This implies that the system will exhibit alternating lag signs for \( n \) harmonics, provided \( t_d \) lies within the range

\[
\pi(1 - 1/m) < \omega_0 t_d < \pi(1 + 1/m), \tag{6}
\]

where \( m = n + 1 \). For example, for a system with four harmonics with alternating lags (like the 67 mHz QPO in GRS 1915+105), the time lag \( t_d \) is restricted to lie between 3/8 and 5/8 of \( 1/\omega_0 \), where \( \omega_0 \) is the fundamental frequency. Note that the phase \( \phi \) depends on function \( \gamma(\omega) \) (Equation (5)) and, in general, could be small even though \( t_d \) is required to be \( \approx 1/\omega_0 \) to satisfy condition (6).

It is useful to enumerate the different conditions that need to exist in a system for this model to be applicable. The first condition is that there needs to be at least two parameters that characterize the spectrum. This is generally true for most radiative models invoked to explain hard X-ray spectra. For example, in the Comptonization model, the spectrum depends on the optical depth and temperature of the Comptonizing region. It should be noted that the spectral parameters \( a \) and \( b \) need not necessarily characterize the same spectral component. For example, \( a \) could characterize a soft (black body-like) component of the spectrum, while \( b \) could be related to the hard X-ray power law that lags the intrinsic one after a time delay. The second condition is that two of the parameters should be related to each other (Equation (2)). Again, it is probably true, in general, that variations in one parameter will induce variations in the other. The third condition is that \( t_d \), the interaction time scale between the two parameters, is of the same order as \( 1/\omega_0 \), where \( \omega_0 \) is the QPO frequency. This would only be true for those phenomena where the QPO-producing mechanism is similar to the one coupling the two parameters. For example, if the QPO is being produced by a dynamic process and the coupling between the two parameters is also of a dynamic nature, then it is expected that \( t_d \approx 1/\omega_0 \approx t_{dyn} \), where \( t_{dyn} \) is the dynamic time scale. Finally, the fourth condition is the restriction on \( t_d \) for the system to show alternating lags (Equation (6)). If the previous three conditions are satisfied for most of the systems, then this final criterion is expected to occur in a fraction of them. It should be emphasized that if there is an observation of alternating lags for a large number of harmonics of a QPO, then for this model to be applicable, \( t_d \) would need to be “fine tuned” to satisfy Equation (6). Therefore, such an observation would indicate that this model is at least not generally applicable. However, for alternating lags up to three or four harmonics, condition (6) is not overly restrictive. When the direct coupling \( D(t) \) is not negligible, the criterion for a system to exhibit alternating lags becomes more complex than Equation (6) and depends on the strength and form of the interaction. In such cases, as shown in the next section, a more detailed calculation of the phase lags is required.

3. APPLICATION TO 67 mHz QPO OF GRS 1915+105

A 67 mHz QPO with the next three harmonics with alternating lags was detected by RXTE during the 1996 May 5 observation of the black hole system GRS 1915+105 (Morgan et al. 1997; Cui 1999). Since the Q factor for this QPO is large.
where so (Equation (1)) is the time-independent part of the spectrum. The first term of the right-hand side of Equation (7) is the linear response of the spectrum to perturbation in $a$ if $s(E) \propto e^{-Ea}$, while the second term is for the case when $s(E) \propto E^{-b}$. Thus Equation (7) corresponds to the situation when the spectrum can be described as an exponentially cut-off power law ($s(E) \propto E^{-b}e^{-Ea}$), with $a$ characterizing the inverse of the cut-off energy and $b$ the power-law slope. In this interpretation, $E_p$ is the pivot energy over which the power-law component varies. This is partly motivated by observations of the high-energy ($E > 3$ keV) time-averaged spectra of some black hole systems that can be approximately described as an exponentially cut-off power law. The time-averaged spectrum for the observation showing the 67 mHz QPO can be roughly (at 2% level) described as a exponentially cut-off power law of index $\sim 1.8$ and cut-off energy $\sim 5$ keV. However, in general, detailed spectral analysis of GRS 1915+105 has shown that its spectrum is generally more complex (e.g., Yadav et al. 1999; Zdziarski et al. 2001; Rodriguez et al. 2008). To avoid such complexities and to keep the temporal model presented here independent of specific spectral models, Equation (7) is used in this analysis with the caveat that the response functions could be significantly more complex in reality. The motivation here is to show that the generic model developed in Section 2 is applicable to the 67 mHz QPO and there exists a simple set of equations that can explain the complex behavior of this phenomenon.

Since harmonics are observed in this system, at least one of the parameters should couple non-linearly to the unknown driving mechanism that produces the QPO. Further, since exactly four harmonics were observed, this suggests that the coupling is of a quartic nature. Hence it is assumed here that

$$\Delta s(E, t) = -E\Delta a(t) - \log(E/E_p)\Delta b(t),$$

(7)

where $s_s(E)$ is the time-independent part of the spectrum. The variations in the photon spectrum $s(E,t)$ are assumed to be linearly driven by variations in two parameters $a$ and $b$ (Equation (1)), such that

$$\frac{\Delta s(E, t)}{s_s(E)} = -E\Delta a(t) - \log(E/E_p)\Delta b(t),$$

where $s_s(E)$ is the time-independent part of the spectrum. The first term of the right-hand side of Equation (7) is the linear response of the spectrum to perturbation in $a$ if $s(E) \propto e^{-Ea}$, while the second term is for the case when $s(E) \propto E^{-b}$. Thus Equation (7) corresponds to the situation when the spectrum can be described as an exponentially cut-off power law ($s(E) \propto E^{-b}e^{-Ea}$), with $a$ characterizing the inverse of the cut-off energy and $b$ the power-law slope. In this interpretation, $E_p$ is the pivot energy over which the power-law component varies. This is partly motivated by observations of the high-energy ($E > 3$ keV) time-averaged spectra of some black hole systems that can be approximately described as an exponentially cut-off power law. The time-averaged spectrum for the observation showing the 67 mHz QPO can be roughly (at 2% level) described as a exponentially cut-off power law of index $\sim 1.8$ and cut-off energy $\sim 5$ keV. However, in general, detailed spectral analysis of GRS 1915+105 has shown that its spectrum is generally more complex (e.g., Yadav et al. 1999; Zdziarski et al. 2001; Rodriguez et al. 2008). To avoid such complexities and to keep the temporal model presented here independent of specific spectral models, Equation (7) is used in this analysis with the caveat that the response functions could be significantly more complex in reality. The motivation here is to show that the generic model developed in Section 2 is applicable to the 67 mHz QPO and there exists a simple set of equations that can explain the complex behavior of this phenomenon.

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$$\Delta a(t) = Ra(1 + \beta \cos(\omega t)),$$

(8)

where $1 + \beta \cos(\omega t)$ is the oscillating driver and $Ra$ is the coupling constant between it and $a$. These variations in $a$ cause variations in $b$ (Equation (2)) with a time delay $\tau_d$,

$$\Delta b(t) = F\Delta a(t - \tau_d) + R_b \beta \cos(\omega t).$$

(9)

Here it is assumed that the direct coupling between the driving oscillation and $b$ ($D(t)$) is linear and in phase with interaction causing $\Delta a(t)$. Equations (7)–(9) can now be solved to obtain the fractional rms amplitude and the phase lag as a function of energy for the fundamental and the next three harmonics. A detailed fitting to the observed data points would require convoluting the predicted time-varying spectrum with the instrumental response function and binning the resultant folded spectrum in appropriate energy bins. However, since the motivation here is to show that qualitative trends in the data can be explained by the model, the theoretical variations are
directly compared with the data points. The results are shown in Figures 1 and 2. The six parameters required for the fit are $E_p$, $R_a$, $\beta$, $F$, $t_1$, and $R_b$. The phase lag as a function of energy for the three harmonics other than fundamental (Figure 2) depends only on three of these parameters, $E_p$, $F$, and $t_1$. The variation of the fractional amplitude with energy of the same harmonics depends on two additional parameters $R_a$ and $\beta$, while the amplitude and phase lag of the fundamental with energy also depends on $R_b$.

It is encouraging to find that the observed relative amplitude of the different harmonics (including the observation that the amplitude of the fourth harmonic is larger than the third) can be further strengthened and/or modified by comparing the predicted values of the phase of the Bicoherence function with the ones inferred from observations. The model also puts restrictions on the radiative and dynamic mechanisms that are operating to produce this phenomenon of alternating lags in QPO harmonics. Physical models developed in the framework of the phenomenological one will enhance our understanding of these systems.

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4. SUMMARY AND DISCUSSION

The phenomenological model presented here should be developed further to incorporate the specific radiative and dynamic mechanism that could be operating for this system. The inferred weak coupling between the parameters ($a$ and $b$) and the driving oscillation ($R_a = 2.3 \times 10^{-6}$ keV$^{-1}$ and $R_b = -7.2 \times 10^{-3}$) could occur if the driving oscillation is localized to some particular radius of the accretion disk and therefore couples weakly with the parameters, which are probably global averages. A localized driver would also naturally explain why the QPO is so narrow (FWHM $\approx$ MHz) since then the frequency could be associated with some natural frequency of the disk at that particular radius. However, it would then be difficult to understand why the time scale of interaction between the two (global) parameters $t_1$ is similar in magnitude to the time scale of the oscillation ($1/f$). If the form of Equation (8) is correct, that would indicate that the physical quantity associated with the driver can have negative values since $b = 9 > 1$. This means that the driving oscillation is not a positive physical quantity like temperature, density, etc., but needs to be associated with a quantity that can have negative values, e.g., accretion rate, viscous stress, etc.

In summary, a generic model for alternating lags for the harmonics of QPO has been presented. Based on the generic model, a phenomenological one has been developed to explain the amplitude and phase lag variation with energy of the harmonics of the 67 MHz QPO observed in GRS 1915+105. The model can be further strengthened and/or modified by comparing the predicted values of the phase of the Bicoherence function with the ones inferred from observations. The model also puts restrictions on the radiative and dynamic mechanisms that are operating to produce this phenomenon of alternating lags in QPO harmonics.

Figures 1 and 2. The six parameters required for the fit are $E_p$, $R_a$, $\beta$, $F$, $t_1$, and $R_b$. The phase lag as a function of energy for the three harmonics other than fundamental (Figure 2) depends only on three of these parameters, $E_p$, $F$, and $t_1$. The variation of the fractional amplitude with energy of the same harmonics depends on two additional parameters $R_a$ and $\beta$, while the amplitude and phase lag of the fundamental with energy also depends on $R_b$.

It is encouraging to find that the observed relative amplitude of the different harmonics (including the observation that the amplitude of the fourth harmonic is larger than the third) can be explained by a simple non-linear equation (8). In particular, the Fourier transform of Equation (8) leads to

$$
\Delta A(\omega) \approx \left( 2 \beta + \frac{3}{2} \beta^3 \right) \delta(\omega - \omega_{2\beta}) + \left( \frac{1}{2} \beta \right)^3 \delta(\omega - 3\omega_{2\beta}) + \left( \frac{1}{16} \beta^3 \right) \delta(\omega - 4\omega_{2\beta}),
$$

which, when combined with Equations (7) and (9), sets the relative amplitude of the different harmonics (Figure 1). However, the interactions chosen here (Equations (8) and (9)) may not be unique and it may be possible that there exists more complex non-linear relationships that give similar results. For example, $a(t)$ could be coupling non-linearly to $b(t)$ instead of the driver, i.e., $a(t) = f_{nl}(b(t))$, where $f_{nl}$ is a nonlinear function. However, such a function would give different phase lags between the harmonics than those computed using Equation (8). The phase lag between the harmonics can be indirectly measured using the phases of the Bicoherence function, which is defined as (Maccarone & Coppi 2002; Maccarone et al. 2011; Maccarone 2013)

$$
B_{nm}(E) = \Delta S_n(E) \Delta S_m(E) \Delta S_{m+n}(E),
$$

where the integer sub script on $\Delta S(E)$ stands for different harmonics. Figure 3 shows the predicted values of the phase of $B_{11}$, $B_{12}$, and $B_{22}$ as a function of energy using Equations (7)–(9). These variations can be directly compared with the observed values to test the validity of these equations and confirm the model developed here. Significant differences from the predicted values would perhaps indicate that the nonlinear equation (8) is more complex than the one assumed in this work.
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