Frequency Dependent Lags - A Common Phenomenon of Accreting Sources

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Abstract. The Fourier frequency dependent hard X-ray lag, first discovered from the analysis of aperiodic variability of the light curves of the black hole candidate Cygnus X-1, turns out to be a property shared by several other accreting compact sources. We show that the lag can be explained in terms of Comptonization process in coronae of hot electrons with inhomogeneous density distributions. The density profile of a corona, like the optical depth and electron temperature, can significantly affect the Comptonization energy spectrum from it. This means, by fitting the energy spectrum alone, it is not possible to uniquely determine the optical depth and temperature of the Comptonization cloud if its density profile is unknown. The hard X-ray time lag is sensitive to the density distribution of the scattering corona. Thus simultaneous analysis of the spectral and temporal X-ray data will allow us to probe the density structure of the Comptonizing corona and thereby the dynamics of mass accretion onto the compact object.

INTRODUCTION

It is well known that the energy spectrum does not provide sufficient information to determine the dynamics of mass accretion in X-ray binaries. This information can be obtained from the independent variability measurements. One of the frequently used variability measures is the phase or time lag of hard X-rays with respect to the soft ones. Because in Comptonization, the energy of the escaping photons increases with their residence time in the scattering medium, the hard photons lag with respect to softer ones by amounts which depend on the photon scattering time. Thus, observations of these time lags provide a measure of the local electron density, a quantity inaccessible to the spectral analysis alone.

Since the high energy radiation is believed to be produced in the vicinity of the compact object of the size of a few Schwarzschild radii, these lags should be roughly of the order ~ msec or shorter. Observations of these lags, however, have given results drastically different from our expectations: The lags measured from the black hole candidate Cyg X-1 obtained by Ginga [1] has revealed that these lags increase linearly with increasing Fourier period to ∆t ∼ 0.1 sec for frequency ω ∼ 0.1 Hz (Figure 1a). Similar results were obtained by the analysis of the higher quality RXTE data from the high state
FIGURE 1. (a) The time lags of hard X-rays (15.8 – 24.4 keV) with respect to soft ones (1.2 – 5.7 keV) obtained from Cyg X-1 data [1] and (b) that of hard X-rays (6 – 28 keV) with respect to soft ones (2 – 6 keV) for the source GRS 1758-258 [4]. The circles and dots represent the measured positive and negative lags respectively. The dash-dotted curve represents the lag predicted based on analytical Comptonization model and assumed corona electron density $10^{16}$ cm$^{-3}$. The three other curves are calculation results for Comptonization in the model coronae that produce the energy spectra shown in Figure 3a.

of the same source [2] (Figure 3b). Analysis of the Ginga data from the source GX 339-4 [3] and the RXTE data from GRS 1758-258 [4], Figure 1b) gave the similar dependence, with $\Delta t$ extending in the latter source to $\sim$ 1 sec for $\omega \sim 0.02$ Hz! Finally, the high energy transient GRO J0422+32 was observed by OSSE during outburst and the lags indicated a similar behavior ( [5], Figure 2a). These results suggest that the frequency-dependent hard X-ray time lags may be a common property of these sources.

THE EXTENDED ATMOSPHERE MODEL

Kazanas, Hua & Titarchuk [6] proposed that the discrepancy between expectation and observation can be resolved if the the corona of Comptonizing electrons is non-uniform and extending over several orders of magnitude in radius. Specifically, they proposed the following density profile for the Comptonizing medium:

$$n(r) = \begin{cases} n_1 & \text{for } r \leq r_1 \\ n_1(r_1/r)^p & \text{for } r_2 > r > r_1 \end{cases}$$

(1)

where the power index $p$ is a free parameter; $r$ is the radial distance from the center of the spherical corona; $r_1$ and $r_2$ are its radii of the inner and outer edges respectively. The density profile of Eq. (1) allows scattering to take place over a wide range of densities, thereby introducing time lags over a similar range of time, leading to the observed $\omega$–dependent lags.

In particular, we considered density profiles with $p = 1$ and $3/2$. A soft photon from a source located near $r \approx 0$ would undergo the scattering process, which increases its energy and introduces hard photon time lags proportional
FIGURE 2. (a) The time lags of hard X-rays (75 − 175 keV) with respect to soft ones (35 − 60 keV) for the source GRO J0422+32, obtained from OSSE observation [5]. The solid curve is obtained from a calculation based on Comptonization in a model corona with $p = 1$, $r_2 = 6.33$ light seconds, $kT_e = 100$ keV and $\tau_0 = 0.25$. The level-off frequency at $\omega \simeq 0.025$ Hz indicates the edge of the corona $r_2 \simeq 1/2\pi\omega$. (b) The time lags of hard X-rays (14.09 − 100 keV) with respect to soft ones (0 − 3.86 keV) for the source Cyg X-1 based on RXTE data [9]. The solid curve is a result from the calculation of Comptonization in a corona with $p = 3/2$, $kT_e = 100$ keV, $\tau_0 = 1.5$ and $r_2 = 5$ light seconds.

to the scattering mean free time in the medium [7]. The majority of the data available to-date (Figures 1a, 1b, 2a and 3b) are consistent with the $p = 1$ density profile. The density profile with $p = 3/2$, implied by the advection-dominated accretion model suggested by Narayan & Yi ([8]) would result in a weaker dependence on Fourier period. There are indications of such a dependence in the recent Cyg X-1 data in its hard state ([9], Figure 2b) and during the transitions [2]. The above arguments, thus, lead us to the notion that these lags can be used to probe the density structure of the corona.

DENSITY PROFILE AND ENERGY SPECTRA

These arguments have been verified by numerical simulation of the spectral-temporal properties of the Comptonization process in media with density profile given by Eq. (1) ([6], [11], [12], [10]). The simulations also show that the density distribution of the Comptonizing electrons can significantly affect the emergent spectrum. Figure 3a displays the energy spectra of Comptonizing coronae of various density profiles with properly chosen optical depths. These coronae give rise to spectra that can fit the BATSE data of Cyg X-1 [13] equally well. This fact shows that fitting the spectra alone does not suffice to determine the optical depth $\tau_0$ if the density profile is unknown. On the other hand, the analysis of the lags between photons in the high and low energy ranges, resulting from Comptonization in the above three coronae, yields widely different results (Figure 3b). Also plotted in the figure are the lags obtained from the RXTE observation [2] whose corresponding photon spectrum is given in Figure 3a. It is obvious that the observation favors the non-uniform
FIGURE 3. (a) Three calculated energy spectra which fit equally well the Cyg X-1 data (crosses) observed by CGRO/BATSE in 1994 [13]. These spectra result from Comptonization in coronae with the same temperature (100 keV) but different optical depths and density profiles: dotted - $p = 0, \tau_0 = 0.5$, solid - $p = 1, \tau_0 = 1.0$ and dashed - $p = 3/2, \tau_0 = 0.7$. The dotted and dashed curves are slightly displaced to separate the otherwise nearly identical curves. Also plotted are RXTE/PCA (circles) and HEXTE (dots) data from the same source observed in 1996 [14]. Both observations were made when Cyg X-1 was in the high state and the energy spectra are consistent with each other except normalization. (b) The time lags of hard X-rays ($13 - 60$ keV) with respect to soft ones ($2 - 6.5$ keV) resulting from Comptonization in the same coronae that produce the energy spectra shown in Figure 3a. The three curves represent the density profiles $p = 0, 1$ and $3/2$ respectively. The time lag between the same energy bands based on RXTE data from Cyg X-1 [2] are also plotted.

electron density distributions, specifically the profile with $p = 1$.

All the fits of the lags in Figures 1a, 2a, 2b and 3b require that the outer edge of the coronae be at a distance as great as $r_2 = 5$ light second, or $10^{11}$ cm! This conclusion is rather inescapable, since the observed lags and energy spectra require scattering free path of the order 1 light second and $\tau_0 \sim 1$ respectively.

It is clear that 1) appropriate modeling of the time properties of accreting compact sources suggests a very different picture than that assumed to-date in modeling their spectra, with direct consequences for the associated dynamics and 2) realistic models must consider the associated time variability properties of the system. The physically meaningful way to model these type of sources is through combined spectral-temporal models.

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