

## CORRELATIONS BETWEEN X-RAY SPECTRAL AND TIMING CHARACTERISTICS IN CYG X-2

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### ABSTRACT

Correlations between the quasi-periodic oscillations (QPOs) and the spectral power-law index have been reported for a number of black hole candidate sources and for four neutron star (NS) sources, 4U 0614+09, 4U 1608-52, 4U 1728-34 and Sco X-1. An examination of QPO frequencies and index relationship in Cyg X-2 is reported herein. The RXTE spectrum of Cyg X-2 can be adequately represented by a simple two-component model of Compton up-scattering with a soft photon electron temperature of about 0.7 keV and an iron K-line. Inferred spectral power-law index shows correlation with the low QPO frequencies. We find that the Thomson optical depth of the Compton cloud (CC)  $\tau$ , in framework of spherical geometry, is in the range of  $\sim 4-6$ , which is consistent with the neutron star's surface being obscured. The NS high frequency pulsations are presumably suppressed as a result of photon scattering off CC electrons because of such high values of  $\tau$ . We also point out a number of similarities in terms timing (presence of low and high frequency QPOs) and spectral (high CC optical depth and low CC plasma temperature) appearances between Cyg X-2 and Sco X-1.

*Subject headings:* accretion, accretion disks – stars: individual (Cyg X-2, Sco X-1) – X-rays: individual (Cyg X-2, Sco X-1) – stars: neutron

### 1. INTRODUCTION

Cyg X-2 is a typical low mass X-ray binary (LMXB) Z-source (see van der Klis 2000 for a review) exhibiting features which can be attributed to Z-sources: Z-shape color-color diagram (CCD), 15-60 Hz quasi-periodic oscillation (QPO) frequencies for horizontal branch oscillations (HBO) and 5-20 Hz frequencies for normal-flaring branches (N/FBO). Large numbers of strong HBO and N/FBO frequencies have been found in power density spectrum (PDS) of this source. One of the particular features of Cyg X-2 as a Z-source is that the Z-track undergoes secular changes (evolution) on the time-scale of days (Kuulkers, van der Klis & Vaughan 1996). There is still no consensus in the community on the nature of these changes.

When considering the components of the X-ray spectrum rather than X-ray colors Kaaret et al. (1998) have demonstrated the clear correlation between kHz QPOs and spectral shape in neutron star (NS) LMXBs. When fitting the X-ray spectra of 4U 0614+09 and 4U 1608-52 with simple power laws, Kaaret et al. (1998) observed a correlation between the index of the power law and the QPO frequency, the larger the index, the higher the QPO frequency. On the other hand Ford et al. (1997) have shown that there is a one-to-one correlation between the flux of the blackbody (BB) component of the X-ray spectrum and the QPO frequency in 4U 0614+09, it worth noting that no such correlation exists between the total X-ray flux and the QPO frequency. One can infer the disk mass accretion rate  $\dot{M}_d$  using the blackbody flux. Combination of these QPO-index and QPO-BB flux correlations imply that the spectral index increases when  $\dot{M}_d$  increases.

Barret (2001) reviewed the broad band (0.1-200 keV) spectral and timing observations of LMXBs performed by Beppo-SAX and RXTE and discussed all of these aforementioned correlations in detail.

Titarchuk & Shaposhnikov (2005), hereafter TS05, suggested that black hole (BH) and NS binaries could be observationally distinguished by the correlation between the spectral indices and QPO low frequencies in the binary X-ray spectra. They reported that there was a correlation between the spectral indices and QPO frequencies in the NS binary (the Atoll-source) 4U 1728-34. TS05 implemented a thorough analysis of spectral and temporal properties of 4U 1728-34 using RXTE data. They studied a spectral evolution of this source from hard spectra at low luminosities to soft spectra at high luminosities. They found that the hardest spectra are described by the sum of Compton upscattering of the disk and NS surface soft photons. These spectra are very similar to the hard-state spectra of black hole candidates (BHCs) but they are softer ( $\Gamma \sim 1.6 \pm 0.1$  for BHC,  $\Gamma \sim 2.1 \pm 0.1$  for NS) as expected from the theory [see, for example, Titarchuk & Fiorito (2004)]. On the other hand the high luminosity soft state spectrum of 4U 1728-34 consists of the sum of two blackbody-like components with color temperatures of about 1 keV and 2.2 keV respectively. The softer blackbody component is presumably related to the disk emission as the harder one is related to the NS compact photosphere emission.

Recently Paizis et al. (2006), hereafter P06, confirmed this spectral evolution picture of NS sources using a sample of twelve NS bright low-mass X-ray binaries observed by INTEGRAL [high-energy ( $> 20$  keV) observations]. Their sample comprises the six Galactic Z-sources and six Atoll-sources, four of which are bright GX bulge sources while two (H 1750-440 and H 1608-55) are weaker in the 2-10 keV range. Comparing their results with those obtained by Falanga et al. (2006) on 4U 1728-34, P06 were able to identify four main spectral states for NS LMXBs (see Fig. 4 in P06): very soft state (e.g. GX 3+1), intermediate state (e.g., GX 5-1), hard/power-law (PL) state (H 1750-440 and H 1608-55) and low/hard state (4U 1728-34).

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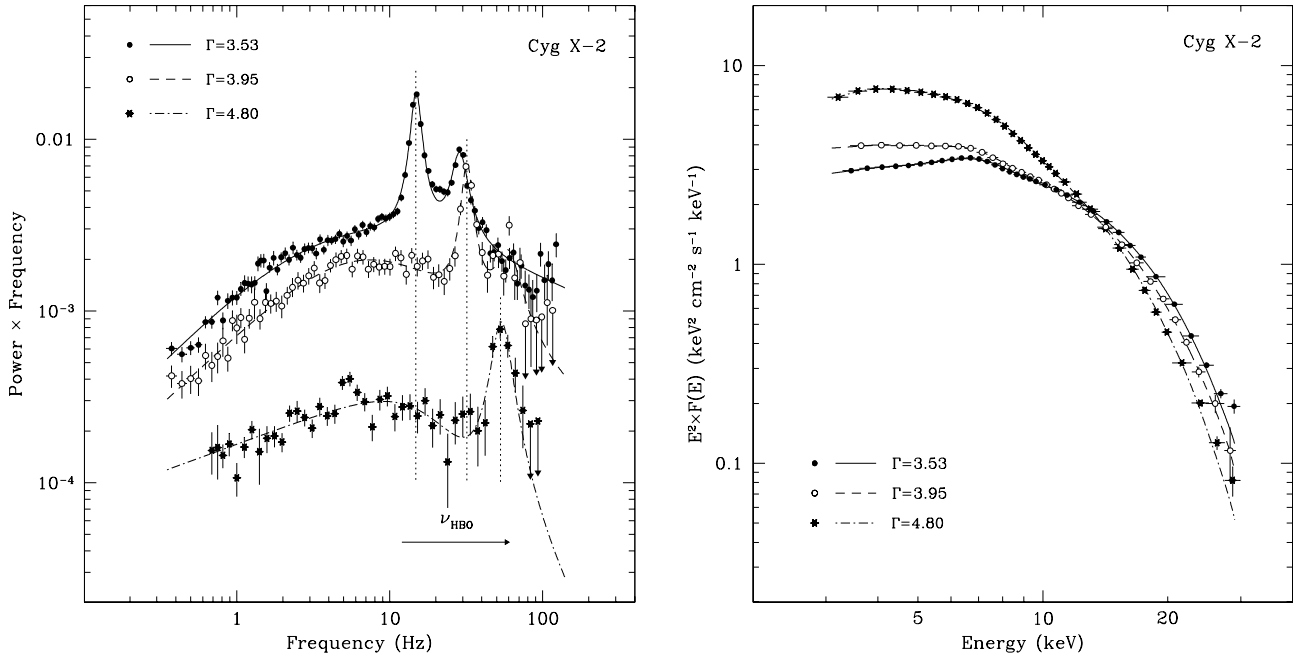


FIG. 1.— Evolution of the power density spectra of Z-source Cyg X-2 and photon spectra. PDSs (left panel) are presented as a  $\nu \times P(\nu)$  diagram (rms/mean)<sup>2</sup>. Photon spectra (right panel) are presented as a  $E^2 \times F(E)$  diagram ( $\text{keV}^2 \text{cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$ ). Power and photon spectra are constructed for the same observational datasets observed with *RXTE/PCA* on March 27, 1996 (filled circles), July 15, 1998 (starred data points) and September 30, 2002 (open circles). Best-fit models of  $\nu \times P(\nu)$  and  $E^2 \times F(E)$  continua are shown by the curves solid curve, dashed curve and dash-and-dotted curve correspondingly. Strong HBO peak of horizontal branch oscillations is a remarkable feature of Cyg X-2 PDS and varies in wide range from 14 Hz to 60 Hz. Best-fit Comptonization models (COMPTT) of photons spectra are related to the Green's function index  $\Gamma$  of  $\sim 3.5$ ,  $\sim 4.0$  and  $\sim 4.8$ .

In P06 the low/hard state spectra are described by thermal Comptonization with plasma temperature  $kT \sim 30$  keV and Thomson optical depth  $\tau \sim 1$ . The hard/power-law (PL) state spectra, as suggested by the name, show simple PL-like emission. The intermediate state spectra are characterized by the presence of a thermal Comptonization component with spectral parameters similar to those of the soft state plus additional PL-like emission above  $\sim 30$  keV. The soft state spectra are described by a single thermal Comptonization component with low  $kT$  and high  $\tau$ .

The power-law state was also found by Piraino et al. (1995), hereafter PSFK, in 4U 0614+09. The steep extended power laws, which indices were about 2.4, were interpreted by PSFK as thermal Comptonization of low energy photons on electrons having a very high temperature  $kT_e$  greater than 220 keV and small optical depth  $\tau$  less than 0.2. However one should realize that the real information in the 4U 0614+09 data is the values of the power-law indices about 2.4 but small optical depth and high electron temperature are a matter of interpretation in terms of the thermal Comptonization model (see §6 for more discussion of this small optical depth interpretation and its relation to non-detection of pulsations from 4U 0614+09).

It is important to emphasize that some of these sources do not undergo the spectral transition from the hard to soft states through the intermediate state but they only evolve within a particular state. Using *RXTE* data Bradshaw, Titarchuk & Kuznetsov (2007), hereafter BTK07, have found that Sco X-1 is always in the high luminosity soft state for which the photon index  $\Gamma$  is between 3.3 and 4.1. The photon spectral model is described by the thermal Comptonization component with low- $kT$ , ranging from 2.5 to 3 keV and high- $\tau$  with values at about 5.1–6 along with a strong 6.4 keV iron line. These results suggest that cooling of Compton

cloud (CC) is dictated by the strong soft emissions coming from the disk and from the neutron star. The photons and plasma are almost in a thermodynamic equilibrium with each other. The CC plasma temperature is very close to the color temperature of the blackbody-like emission of the NS compact photosphere (see e.g. Titarchuk 1994a). Furthermore BTK07 demonstrate the distinct presence of a correlation between QPOs and photon index in Sco X-1 similar to the previously reported correlation in 4U 1728-34. This observed correlation of kHz frequencies with photon index in Sco X-1 (BTK07, Fig. 3) leads to the conclusion that the CC contracts when the source evolves to the softer states.

Hasinger & van der Klis (1989) noted that there is a similar correlation between the fast time variability and the source position along the track described in the color diagram (its color) for both high and low luminosity sources. In this paper we suggest that in high-luminosity LMXBs like Cyg X-2 and Sco X-1 *index-QPO correlations* should be similar because the physical processes producing the power and photon spectra are similar in these sources.

A phenomenological classification of the aperiodic and quasi-periodic variability in LMXBs has been already given in the literature, and it is also shown that these features behaves in a similar way in Z- and atoll-sources and perhaps also in black hole candidates [see e.g. Wijnands & van der Klis (1999); Psaltis, Belloni & van der Klis (1999)].

Titarchuk, Osherovich & Kuznetsov (1999) applied the transition layer (TL) model [see Titarchuk, Lapidus & Muslimov (1998), Osherovich & Titarchuk (1999), Titarchuk & Osherovich (1999)] to Sco X-1's power spectra. They offered a scheme which allows the classification of the power spectral features if the twin kHz QPO frequencies are observed along with the low QPO frequencies. In this work we also adopt this

TABLE 1  
RESULTS FOR SELECTED RXTE OBSERVATIONS

| Observation ID<br>(orbit)          | T Start<br>(MJD) | T Obs.<br>(ks) | $\nu_L$<br>(Hz)  | $kT$<br>(keV)   | $\tau$          | $\Gamma$        | $\chi^2_{red}$ ( $N_{dof}$ ) |
|------------------------------------|------------------|----------------|------------------|-----------------|-----------------|-----------------|------------------------------|
| 10066-01-01-00.4 (●) <sup>a</sup>  | 50169.6315       | 3.0            | $14.83 \pm 0.03$ | $2.98 \pm 0.01$ | $5.68 \pm 0.01$ | $3.53 \pm 0.01$ | 0.96 (52)                    |
| 70104-02-02-00.1 (○) <sup>a</sup>  | 52547.8956       | 1.4            | $31.90 \pm 0.18$ | $2.94 \pm 0.03$ | $5.04 \pm 0.06$ | $3.95 \pm 0.05$ | 0.64 (46)                    |
| 30046-01-01-00.4 (* <sup>a</sup> ) | 51009.6857       | 3.3            | $53.09 \pm 0.97$ | $2.71 \pm 0.01$ | $4.23 \pm 0.01$ | $4.80 \pm 0.01$ | 1.03 (52)                    |

<sup>a</sup> These symbols mark the corresponding data points on Figs. 1, 3 and 4

classification. In section 3 we show that the power spectra of Sco X-1 and Cyg X-2 are similar. Break frequency ( $b$ ), horizontal branch oscillation (HBO) frequency harmonics ( $L$ ,  $2L$ ), lower kHz (Keplerian) ( $K$ ) and higher (hybrid) ( $h$ ) frequencies are clearly seen in the Cyg X-2 PDSs. The lowest peaks in Sco X-1 and Cyg X-2 PDSs are identified in the TL model as a frequency of magneto-acoustic (viscous) oscillations ( $\nu_V$ ).

In Cyg X-2 (similar to Sco X-1) we find that the high/soft state spectra (photon spectral index) varies when the low QPO frequencies change at least by factor of 2. Description of observations, data reduction and analysis are presented in §2. Description of Cyg X-2 power spectra and QPO identification are presented in §3. Details of our spectral fitting are presented in §4 and we discuss a correlation of low QPO frequency vs photon index revealed in Cyg X-2 in §5. Discussion and conclusions follow in §6 and §7.

## 2. OBSERVATIONS, DATA REDUCTION AND ANALYSIS

In the present work we use Cyg X-2 data collected by RXTE/PCA (Jahoda et al. 1996) during following cycles of pointing observations: 10063, 10065, 10066, 10067, 20053, 30046, 30418, 40017, 40019, 60417, 70014, 70016, 70104. Our data set comprises 760 ksec total on-source time. For our analysis we extract PDS and energy spectrum for each RXTE orbit revolution.

To construct PDSs we used observational data with a resolution of  $\sim 122\mu\text{s}$  (and better) from all 249 PCA energy channels. We combined some of the observational data that were not presented in a single format for all 249 channels. Double event data were also used and merged when they are available. Among the observations of Cyg X-2, all five proportional counters were not always switched on to record events. If the operating condition of one of the counters changed during a continuous observation, then the time interval during which the total count rate changed abruptly was excluded from our analysis. Note duration of the a continuous observation did not exceed the duration of one orbit which was, on the average, 3–3.5 ks. As a result of this filtering, the total usable observational time for Cyg X-2 was more than 760 ks.

We constructed PDSs in the range 0.03125–128 Hz to analyze the low-frequency ( $< 100$  Hz) variability of Cyg X-2 and in the band 128–2048 Hz to search for kHz QPO peaks.

No corrections were made for the background radiation and dead time. We added a constant to the general model [see details in Vikhlinin et al. (1994)] to take into account the PCA deadtime effect, which causes the overall level to be shifted to the negative region.

Fitting PDSs by a sum of constant and broken power law function did not give acceptable results (according to the  $\chi^2$  test). The transition between two slopes in PDS is rather smooth which results in high residuals in the vicinity of the

break frequency and large resulting uncertainty in its measurement. A phenomenological model which we use to fit the PDS continuum was more suitable

$$P(\nu) = A\nu^{-\alpha} [1 + (\nu/\nu_b)^\beta]^{-1}. \quad (1)$$

For spectral analysis we accumulate the energy spectra from Standard2 PCA data mode using the FTOOLS software package (Blackburn 1995) and PCA Energy spectra were also deadtime corrected according to "The RXTE Cook Book"<sup>4</sup>.

We model the energy spectra using XSPEC astrophysical fitting package in the energy range of 3–30 keV with an added systematic error of 1%. The modeling results produced an average reduced  $\chi^2$  ( $\chi^2$  divided by the degrees of freedom)  $\chi^2_{red} \sim 1$  across all OBSIDs. The spectra were modeled in XSPEC with a two-component additive model consisting of a Comptonization (COMPTT model in XSPEC, see Titarchuk 1994b; Hua & Titarchuk 1995) and an Iron  $K_\alpha$  line (Gaussian) model (Figure 1, right panels). A value for the photon index  $\Gamma$  ( $\Gamma = \alpha + 1$ ) was inferred from the modeling results, where  $\alpha$  and  $\gamma$ , for spherical geometry of the Compton cloud, are determined by

$$\alpha = -3/2 + \sqrt{9/4 + \gamma}, \quad (2)$$

$$\gamma = \pi^2 m_e c^2 / [3(\tau + 2/3)^2 kT] \quad (3)$$

using the diffusion solution by Sunyaev & Titarchuk (1980). The values for optical depth  $\tau$  and electron temperature  $kT$  are determined from the COMPTT model parameters and  $m_e c^2 = 511$  keV. Error bars of  $\Gamma$ -values were determined using the errors of  $\tau$  and  $kT$ . We present the results of our spectral analysis along with QPO frequency for three representative observations in Table 1.

## 3. POWER SPECTRUM AND QPO IDENTIFICATION

Figure 1 illustrates the evolution of PDSs, observed with RXTE/PCA on March 27, 1996 (filled circles), July 15, 1998 (starred data points), September 30, 2002 (open circles) and the photon spectra. The dash-dotted lines in Figure 1 depict a continuum fit to the HBO power spectra. In Figure 2 we show that the power spectra of Sco X-1 and Cyg X-2 are similar.

It is worth noting that the PDS's continuum power decreases as the spectral state softens. Strong HBO features are clearly seen in each  $\nu \times$  PDS diagram. HBO peaks of Cyg X-2 PDSs vary in a wide range from from 14 Hz to 60 Hz. Both lower and upper kHz QPO peaks are detected simultaneously only in an observation carried out on July 2, 1997 [see details of the data analysis and QPO identification in Kuznetsov (2001)]. We obtain the high frequency QPO values  $\nu_K = 464.9 \pm 13.4$  Hz,  $\nu_h = 830.7 \pm 12.7$  Hz, with significances  $3.4\sigma$  and  $5.8\sigma$  for the QPO low and the

<sup>4</sup> [http://heasarc.gsfc.nasa.gov/docs/xte/recipes/cook\\_book.html](http://heasarc.gsfc.nasa.gov/docs/xte/recipes/cook_book.html)

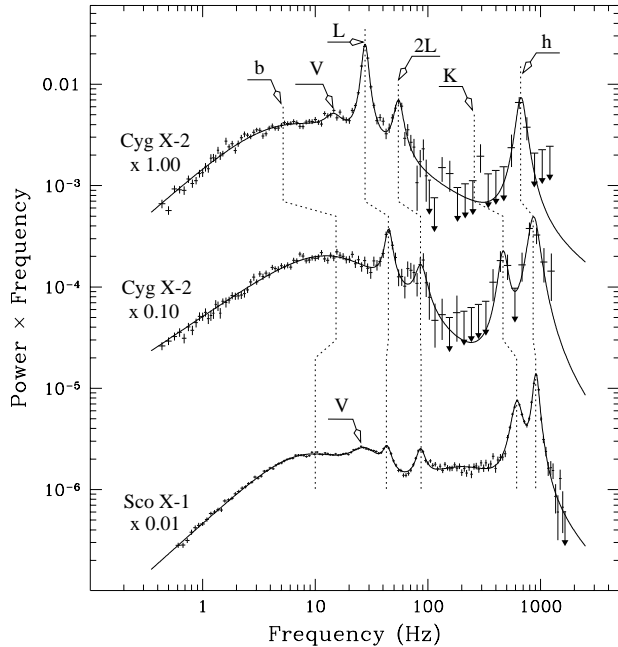


FIG. 2.— Power Density Spectra of Z-sources Cyg X-2 (as a result of the presented study) and Sco X-1 [adopted from Titarchuk, Osheroich & Kuznetsov (1999)] in units of  $\nu \times P(\nu)$ , (rms/mean)<sup>2</sup>. Upper limits correspond to  $1\sigma$  confidence level. Break frequency (*b*), frequency of magnetoacoustic oscillations ( $\nu_V$ ), HBO frequency harmonics (*L*,  $2L$ ), Keplerian (*K*) and hybrid (*h*) frequencies are marked. Similar features in all power density spectra are connected by dotted lines. Predicted value of Keplerian frequency in the top spectrum is shown. Lower peak in Sco X-1 spectrum is shown as a frequency of viscous oscillations  $\nu_V$  (see text for details).

high frequencies respectively and the value of HBO peak,  $\nu_L = 44.70 \pm 0.35$  Hz, with a significance of  $7.7\sigma$ .

Upper peak was rarely detected in observations corresponding to the source position on HBO of Z-track.

#### 4. X-RAY SPECTRA

The sum of Comptonization and iron line components well describes the Cyg X-2 X-ray energy spectrum. The  $N_H$  column was frozen at Galactic value  $0.22 \times 10^{22}$  cm<sup>-2</sup> [see Dickey & Lockman (1990)].

Iron  $K\alpha$  line energy was fixed at 6.4 keV. The width of the line was about 1 keV. The Gaussian equivalent width (EW) varies from 150 eV to 450 eV, showing a tendency to increase towards the soft state, similar to BTK07 findings for Sco X-1. However RXTE energy resolution is poor at low energies and therefore the results for Iron line parameters should be interpreted carefully.

The EW of the iron line can be also sensitive to the continuum model. We obtain this result using COMPTT alone whereas other results in the literature estimated this EW using much more complicated continuum models. For example Di Salvo et al. (2002) reported on the results of a broad band (0.1–200 keV) spectral study of Cyg X-2 using two Beppo-SAX observations taken in 1996 and 1997 respectively. These Beppo-SAX spectra are fitted to a model consisting of a disk blackbody, a Comptonization component, and two Gaussian emission lines at 1 keV and 6.6 keV, respectively. The addition of a hard power-law tail with photon index 2, contributing 1.5% of the source luminosity. The second emission line, presumably  $K\alpha$  line at an energy of 6.6–6.7

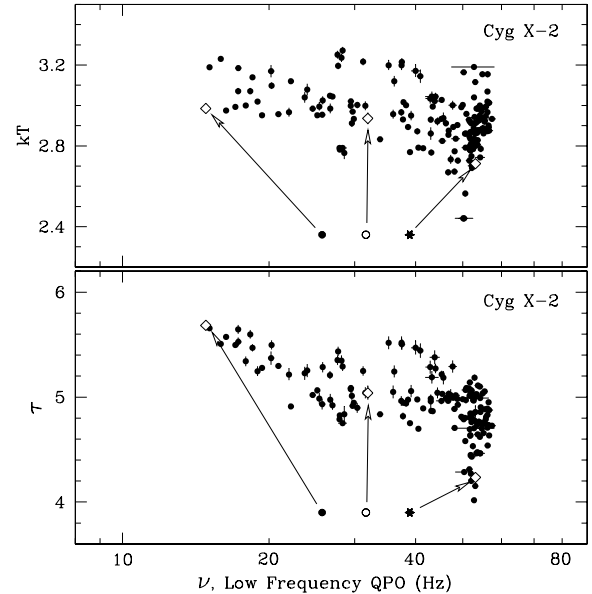


FIG. 3.— Best-fit Comptonization model parameters (xspec: COMPTT) versus frequency of HBO peaks in Cyg X-2.  $kT$  is the electron CC temperature and  $\tau$  is optical depth of CC cloud. Open diamonds are the same observational datasets as shown in Figure 1.

keV has equivalent widths from 24 to 55 eV. This value is lower than that we found using only COMPTT component for the RXTE data. However our results in agreement with claims by Di Salvo et al. (2002), Kuulkers et al. (1997) and Smale et al. (1993) that the addition of the iron  $K\alpha$  is required to fit the spectrum of Cyg X-2.

For the COMPTT model we use spherical geometry. We obtain the seed photon temperature ( $T_0$ ) in the range 0.5–0.8 keV. In Figure 3 we present the best-fit COMPTT parameters  $\tau$  and  $kT$  versus the observed HBO frequency. We find that the Compton cloud (CC) optical depth values varies in the range of 4–5.8 as the CC electron temperature varies in the range of 2.4–3.2 keV. It is worth noting that these temperature values are very close to the color temperature of blackbody emission of the NS compact photosphere (see e.g. Titarchuk 1994a). It implies that the plasma is very close to equilibrium with the photon field in the NS environment (CC). On the other hand high  $\tau$ – values lead to the conclusion that any high frequency oscillations ( $\gtrsim 400$  Hz) originating at the NS surface must be suppressed by photon scattering in the Compton cloud and are thus unlikely to be detected [Titarchuk et al. (2002)]. This statement is probably true for all the Z-sources, for which high values of  $\tau$  are usually found [see e.g. Di Salvo et al. (2002), BTK07].

Although  $\tau$  and  $kT$  do not show clear correlations with the QPO low (HBO) frequencies  $\nu_{low}$  (see Fig. 3) there is a well-established correlation between photon index  $\Gamma$  and  $\nu_{low}$ .

#### 5. CORRELATION OF HBO FREQUENCIES WITH PHOTON INDEX

Figure 4 depicts the low-frequency (HBO) and  $\Gamma$  correlation revealed in Cyg X-2 for which the Spearman Rank-Order correlation coefficient  $r_{sro}$  is 1 with the high precision ( $r_{sro} = 0.9998$ ). Photon index  $\Gamma$  was calculated using  $\tau$ ,  $kT$  (presented in Fig. 3) and Eq. (3). A similar correlation of QPO vs  $\Gamma$  in the high/soft state was found in 4U 1728–34 by TS05. The set of  $\Gamma$ ,  $\nu_{low}$  related to the soft states of

4U 1728-34 and Cyg X-2 are located in the right upper corner of  $\Gamma - \nu_{low}$  diagram.

In 4U 1728-34 the index-QPO correlation was found during evolution of the source from low/hard state ( $\Gamma \sim 2$ ) to soft state ( $\Gamma \gtrsim 4$ ). In contrast, Cyg X-2 and Sco X-1 (BTK07) always show a soft spectrum and index-QPO correlation, as  $\Gamma$  changes from 3.3 to 4. The Cyg X-2 and Sco X-1 photon indices  $\Gamma = 3.3 - 5$  are very close to that in the soft state of 4U 1728-34. However, in both NS systems, inferred  $\Gamma$  of the softest state (4–5) is substantially higher than that of the soft state of black holes ( $\sim 2.8$ ).

In the Z-source Cyg X-2 (filled circles) and the Atoll-source 4U 1728-34 (open circles) observations demonstrate no saturation effect at higher QPO frequencies. Dashed lines schematically represent upper and lower ranges of  $\Gamma$  vs  $\nu$  variations in Cyg X-2. Open diamonds are the same observational datasets as shown in Figure 1. In Figure 4 (bottom panel) we present a correlation between photon index  $\Gamma$  and QPO low frequency in Cyg X-1, GRS 1915+105 (short-dash-dotted curve) and XTE J1550-564 (long-dash-dotted curve) [see details in Shaposhnikov & Titarchuk (2006), hereafter ST06].

A saturation effect is a remarkable feature among black holes and it is observed when photon index reaches its maximum value at higher QPO frequencies. The index saturation occurs when the total (disk plus sub-Keplerian) mass accretion rate (in Eddington units,  $\dot{M}_{Edd} = L_{Edd}/c^2$ ) is more than 5 [see details in Titarchuk & Zannias (1998) and Titarchuk & Fiorito (2004), hereafter TF04].

This saturation effect in BHC sources, which is presumably due to photon trapping in the converging flow, can be considered to be a BH signature. We want to stress that this saturation is a model-independent phenomenon found in the analysis of the RXTE data. On the other hand, the saturation of the index with mass accretion rate increase (which is strongly related to the QPO frequency increase) has to apply to any BH because the photons are unavoidably trapped in the accretion flow into BH. In high/soft state of BH the photon trapping effect in converging flow should be very strong because the matter goes into a BH horizon and nothing comes out. Photons are rather taken by the flow than they emerge. It is a necessary condition of BH presence in the accreting systems.

Thus, the index saturation with QPO frequency seen in the source (rather than the presence of the extended hard tail in the soft state) is a signature of the horizon. In fact, one can see high-energy tails with indices at about the BH saturation value of 2.8 in high state observations of weakly magnetized accreting NS binaries, for example, GX 17+2 [Di Salvo et al. (2000), Farinelli et al. (2005) and 4U 1728-34 (TS05)]. Di Salvo et al. (2000) presented seven spectra of GX 17+2 observed in 1999 by Beppo-SAX. They show this hard tail component in GX 17+2 gradually faded as the source moved toward the normal branch (i.e. when the mass accretion rate in disk increases) where it was no longer detectable.

TS05 analyzing RXTE archival data for 4U 1728-34 and we (in the presented paper) analyzing RXTE data for Cyg X-2 reveal the spectral evolution of the Comptonized blackbody spectra and QPO frequencies. Contrary to the BH sources, the indices of the 4U 1728-34 and Cyg X-2 spectra do not saturate as the QPO frequency increases (see Fig. 4 for Cyg X-2 case). They increase from 2 to 6 and from 3.3 to 5 in the 4U 1728-34 and Cyg X-2 correlations respectively with no signature of saturation versus QPO frequency (or mass accre-

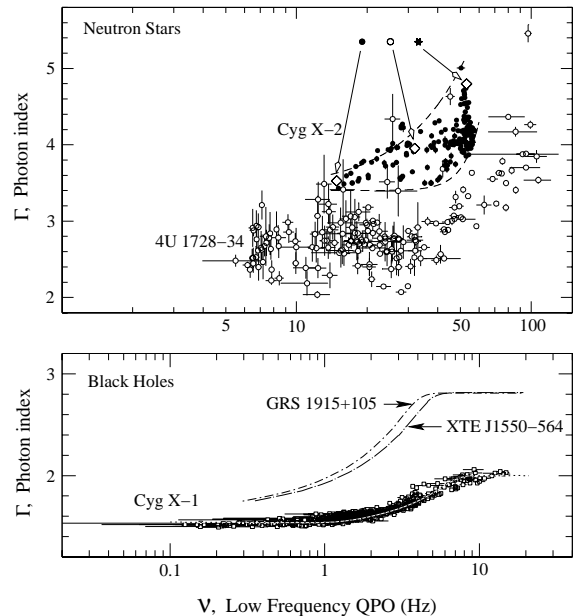


FIG. 4.— Photon index  $\Gamma$  as a basic characteristic of hardness of the energy spectrum vs low frequency QPO of X-ray flux in the Neutron stars (top) and Black holes (bottom) (see text). *Top*: Z-source Cyg X-2 (filled circles) and Atoll-source 4U 1728-34 (open circles) observations demonstrate no saturation effect at higher QPO frequencies. Dashed lines schematically represent upper and lower ranges of  $\Gamma$  vs  $\nu$  variations in Cyg X-2. Open diamonds are the same observational datasets as shown in Figure 1. *Bottom*: Cyg X-1 observational data points and best-fit model shapes to Cyg X-1 (dotted curve), GRS 1915+105 (short-dash-dotted curve) and XTE J1550-564 (long-dash-dotted curve) data demonstrate correlation between photon index  $\Gamma$  and Low-Frequency QPO [adopted from Shaposhnikov & Titarchuk (2006)]. Saturation effect is remarkable feature among black holes and is observed when photon index reaches its maximum value at higher QPO frequencies.

tion rate). The NS soft/state spectrum consists of blackbody components that are only slightly Comptonized (the inferred photon indices of the Comptonization Green's function are  $\Gamma \gtrsim 5$ ). Thus, one can claim (as expected from theory) that in NS sources the thermal equilibrium is established for the high mass accretion rate (soft) state. In BHs the equilibrium never established because of the presence of the event horizon. The emergent BH spectrum, even in the soft state, has a power-law component with an index that saturates with mass accretion rate. It is worth noting that there is a particular state in a BH source in which it can show signs of thermal equilibrium: the emergent spectrum consists of one or two thermal components. But no QPO is observed then. In this (very soft, thermal dominated) state the source is presumably covered by a powerful wind [see Titarchuk, Shaposhnikov & Arefiev (2007) hereafter TSA07] that thermalizes the radiation of the central source and prevents us from seeing any QPO generated in the source (see Fig. 6 in ST06).

We would like to emphasize once again that bulk inflow is present in a BH when the mass accretion is high, but not in an NS, where the presence of the firm surface leads to a high radiation pressure, which eventually stops the accretion. The bulk inflow and all its spectral features are absent in NS soft state; in particular, the saturation of the index with respect to QPO frequency, which is directly related to the optical depth and mass accretion rate, is observed in the soft spectral state of only BHs and is therefore a particular signature of a BH.

Thus the soft state index-QPO correlation can be a tool to determine the nature of the compact object. Due to the pres-

ence of a firm surface, in NS sources photon field is approaching the equilibrium with surrounding plasma as the source enters the high/soft state (when  $\Gamma$ -value increases with QPO frequencies or with mass accretion rate). In a BH source, however, solid surface is replaced by event horizon, i.e. we have a drain instead of stopping boundary.

## 6. DISCUSSION

In this paper we present the results of simultaneous timing and spectral analysis of the NS Z-source Cyg X-2. The energy spectrum is well described by the thermal Comptonization model (COMPTT). The only additional component needed is the iron  $K_{\alpha}$  line at  $\sim 6.4$  keV. This model fits all observations for all spectral states of Cyg X-2. The model parameters are the optical depth and temperature of the Compton cloud which allows us to infer the photon index  $\Gamma$  with rather small errors.

We found that our results for Cyg X-2 are very similar to findings of the BTK07 for Sco X-1, where authors also successfully applied COMPTT model to Sco X-1 RXTE data [see also Di Salvo et al. (2002) for application of COMPTT model to the broad energy band Beppo-SAX data from NSs]. This strongly suggests that both Sco X-1 and Cyg X-2 form their spectra in similar environments. Additionally, the modeling results strongly suggests that Sco X-1 and Cyg X-2 are always in the soft state, where photon index  $\Gamma$  is between 3.3 and 5. Cooling of Compton cloud is dictated by the strong soft emission of the disk and neutron star.

*High frequency pulsations originating at the NS surface cannot be observed because of the CC optical depths in Sco X-1 and Cyg X-2, are much greater than 1.* The NS high frequency pulsations are suppressed because of photon scattering off cloud electrons. This leads to a significant conclusion that *the observed high (kHz) QPOs are detected by the Earth observer because they originate at the outer boundary of the CC.* The NS emission, a  $\sim 2.2$  keV blackbody, is not seen at all in contrast to that of 4U 1728-34 (TS05).

One can ask a fair question why we do not see high frequency pulsations in atoll-sources in the hard state. In fact, the pulsated NS emission is attenuated by scattering off electrons of the Compton cloud and the detected signal consists of two components, the directed and the scattered ones. The directed component is exponentially attenuated with attenuation factor  $\exp(-T)$  where  $T$  is optical path along the line of sight. Thus even the CC optical depth is between 1 and 2 in the hard state of atoll-sources the optical path along the line of sight can be a factor 2-3 more, i.e.  $T = 2-6$  and consequently the directed component would be barely visible. On the other hand the pulsations of scattered component is completely washed if the CC optical depth more than two and the CC geometrical thickness is order of few times of NS radius [see Titarchuk et al. (2002)].

Gogus et al. (2007) recently tried to revisit this Compton scattering scenario to explain lack of pulsations in the majority of LMXBs. They use archival data of RXTE observations of three representative LMXBs (GX 9+9, GX 9+1, and Sco X-1) covering the full range of atoll/Z phenomenology. They argue that the optical depth of the Compton region (corona) in these sources does not exceed  $\tau \lesssim 0.2-0.5$  unless the electron temperature is very low,  $kT_e < 20$  keV. Ultimately Gogus et al. (2007) conclude that lack of coherent pulsations cannot be attributed to the electron scatterings because such small values of the optical depth (that they inferred) are by far insufficient to suppress the pulsations.

On the contrary if the electron temperature of the corona is low as that is in our scenario (see Fig. 3, top) then the Compton cloud is optically thick [see Fig. 3, bottom, Di Salvo et al. (2000), Gogus et al. (2007)]. In addition if the NS surface is surrounded by the quasi-spherical cloud (which is presumably the case for the sources in the high/soft state) then the NS pulsations are completely washed out.

The low frequency oscillations that are detected from Cyg X-2 and Sco X-1 can be also considered as observational evidence of the presence of the bounded Compton cloud in these sources (see details in TSA07).

Another interesting example of the small optical depth interpretation was presented by PSFK. As we emphasize in Introduction section that the real information in the 4U 0614+09 data is a detection of the extended power laws which indices are about 2.4 but small optical depth and high electron temperature are a matter of interpretation in terms of the thermal Comptonization (TC) model. In fact, BTK07 show that the spectral index  $\alpha = \Gamma - 1$  is a reciprocal of the Comptonization parameter  $Y$  which is a product of average number of scattering  $N_{sc}$  and average fractional energy change per scattering  $\eta$ . As for TC  $\eta = 4kT_e/m_e c^2$ , i.e independent of  $\tau$  whereas for the converging (diverging) flow (CF)  $\eta$  is inverse proportional to  $\tau$  (see e.g. Laurent & Titarchuk 2007). It implies that even when the CF  $N_{sc}$  is large, the  $Y$ -parameter (or  $\Gamma$ ) can saturate to some low value because  $N_{sc}$  is proportional to  $\tau$  in this case. In contrast, in the TC case one needs to keep  $\tau$  at small values in order to have values of  $Y$  about  $1/\alpha \approx 1/1.4 \approx 0.7$  since the high energy cutoff requires  $kT_e \sim 200$  keV (see PSFK). In fact,  $N_{sc} \approx Y/\eta$  and  $\tau \approx Y/(2\eta)$  because  $N_{sc} \approx 2\tau$  in the TC case. Then one obtains a value of  $\tau \approx Y/(2\eta) \approx 0.7/3.2 \approx 0.2$  which is similar to that using the TC model (see PSFK).

Titarchuk & Farinelli 2007 (in preparation) made extensive calculations of the hydrodynamics of the transition layer (Compton cloud) presumably located between the neutron star surface and geometrically thin Keplerian disk. They found that in the innermost part of the transition layer (TL) of the size about NS radius the matter is almost in free-fall regime. Probably the hard spectra detected from 4U 0614+09 are rather formed in this TL region than they are a result of the thermal Comptonization in some optically thin corona surrounding neutron star. The real optical depth of the Compton cloud (CC) can be large given that the 4U 0614+09 observations show a relatively high temperature of the blackbody component of about 1.5 keV. Such a high temperature is definitely related to the NS surface temperature and it can be only in the state when mass accretion rate, and consequently CC optical depth, is high. Thus, it is not by chance, we do not see pulsations from 4U 0614+09 because they are presumably blocked by optically thick Compton cloud.

## 7. CONCLUSIONS

We demonstrate a definite correlation of QPOs with photon index in Cyg X-2 which has no sign of the index saturation at high values of QPO frequency. The similar correlations were previously reported in four NSs: 4U 0614+09, 4U 1608-52, 4U 1728-34 and Sco X-1.

The observed correlations of QPO frequencies with photon index in the NS soft state lead us also to conclude that the Comptonization efficiency is suppressed in the high/soft state of Cyg X-2, namely the disk and NS photons reach almost an equilibrium with surrounding plasma of the Compton cloud.

In the BH high/soft state conversely, the index saturates with QPO frequency (actually with mass accretion rate). In

terms of the Physics of photon-plasma interaction this implies that photons are trapped in converging flow i.e. they are driven by the flow across an event horizon rather than emerging. The bulk motion Comptonization (upscattering) efficiency saturates with the mass accretion rate.

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