DISCOVERY OF RED-SKEWED $K_\alpha$ IRON LINE IN Cyg X-2 WITH SUZAKU

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ABSTRACT

We report on the 

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observation of neutron star (NS) low-mass X-ray binary Cygnus X-2 which reveals a presence of the iron $K_\alpha$ emission line. The line profile shows a significant red wing. This discovery increases the number of NS sources where red-skewed iron lines were observed and strongly suggests that this phenomenon is common not only in black holes but also in other types of accreting compact objects. We examine the line profile in terms of models which attribute its production to the relativistic effects due to reflection of X-ray radiation from a cold accretion disk and also as a result of the line formation in the extended wind/outflow configuration. Both models are able to adequately represent the observed line profile. We consider the results of line modeling in the context of subsecond variability. While we were unable to conclusively disqualify one of the models, we find that the wind paradigm has several advantages over the relativistic disk reflection model.

Key words: accretion, accretion disks – stars: neutron – X-rays: individual (Cygnus X-2)

1. INTRODUCTION

Recent discoveries of red-skewed iron lines in spectra of neutron star (NS) sources Serpens X-1 (Bhattacharyya & Strohmayer 2007), 4U 1820–30, GX 349+2 (Cackett et al. 2008, C08 hereafter), and 4U 1636–536 (Pandel et al. 2008) show that the phenomenon of red-skewed lines is not restricted to black hole (BH) sources. In this paper, we report on the discovery of the asymmetric iron line in the 

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spectrum of the NS source Cygnus X-2 (Cyg X-2). Therefore, Cyg X-2 is the fifth NS source which shows asymmetric iron line profile. This indicates that the red-skewed lines in NS sources may be as common as in BH sources. More generally, asymmetric emission lines appear to be abundant in both types of accreting powered X-ray sources. It is crucial to correctly identify the physical origin of the red skewness of these lines because they can be potentially used to study the properties of the accretion close to accreting objects as well as to constrain the fundamental characteristics of compact objects.

C08 interpreted the $K_\alpha$ iron line profiles in terms of relativistically redshifted emission due to reflection off the accretion disk very close to a compact object. This scenario is commonly accepted as an explanation of strongly red-skewed iron lines in BH sources (Miller 2007). The main motivation for applying the relativistic line formation scenario to the NS case was the fact that the inner radius of the accretion disk, which was predicted by the relativistic line model was consistent with the interpretation of the highest observed kilohertz quasi-periodic oscillation (kHz QPO) frequency in these sources as a Keplerian frequency at this radius.

A red-skewed profile of emission lines can be also produced by repeated electron scattering in a diverging outflow as proposed by Laurent & Titarchuk (2007, LT07 hereafter); see also references therein. In the framework of the wind model the fluorescent iron line is formed in the partly ionized wind as a result ofillumination by the central source. Electron scattering of the iron $K_\alpha$ photons within the ionized expanding flow leads to a decrease of their energy (redshift). This photon redshift is an intrinsic property of any outflow for which divergence is positive. Recently Sim et al. (2008) confirmed using multidimensional Monte Carlo (MC) simulation that for sufficiently high wind densities, moderate Fe $K_\alpha$ emission lines can be formed and that electron scattering in the flow may cause these lines to develop extended red wings.

We examine the red-skewed line profile observed in Cyg X-2 both in terms of the relativistic paradigm and in the framework of the wind downscattering. The main obstacle in analyzing the high spectral resolution data with the wind model is that analytical solution is not available for the general formulation of this problem. LT07 used MC simulations to model the line profiles produced in the wind environment. In the presented work, we provide a consistent analysis of the line profile with the wind model by introducing the LT07 MC code into XSPEC astrophysical data analysis package. We find that the wind-outflow model is able to reproduce the red-skewed line profile with the fit quality similar to that shown by the relativistic reflection models. Therefore, in order to distinguish between these two models one has to consider their consistency in a broader phenomenological context. For example, C08 proposed to look for high-frequency quasi-periodic oscillations (HF QPOs) as an additional evidence of a Keplerian disk existence close to an NS, which then would necessitate the presence of the reflection components in energy spectra. In contrast, the presence of the opaque wind in the system would result in smearing the signal coming from the central region. This smearing effect leads to a suppression of the fast variability of X-ray emission. Unfortunately, high time resolution observations by 

Rossi X-ray Timing Explorer (RXTE)

, simultaneous with the 

Suzaku

observations analyzed in this paper, are not available. Thus, we resort to a study based on the 

RXTE

data set with similar spectral characteristics. Our comparative analysis indicates that the source was in a low variability state during
these observations which is more consistent with the wind/outflow scenario.

Description of the \textit{Suzaku} and supporting \textit{RXTE} observations, as well as details of our spectral fitting, is presented in Section 2. We discuss implications of the relativistic and wind-outflow as well as details of our spectral fitting, is presented in Section 2. Conclusions follow in Section 4.

2. OBSERVATIONS AND SPECTRAL MODELING

Cyg X-2 is a low mass X-ray binary (LMXB; 1995, for review) which exhibits a Z-shape color–color diagram (Hasinger & van der Klis 1989). The observations of thermonuclear X-ray bursts (Smale 1998) identified the nature of the compact object in Cyg X-2 as a neutron star. Titarchuk & Shaposhnikov (2002) used the \textit{RXTE} burst data to estimate the NS mass to be about 1.4 solar masses and radius to be about 9 km. Wijnands et al. (1998) reported the simultaneous detection of twin kHz peaks at 500 and 860 Hz and highest single kHz QPO at 1007 Hz.

Cyg X-2 was observed by \textit{Suzaku} (Mitsuda et al. 2007) on 2006 May 16 for a total exposure of 39 ks (Observation ID: 401049010). However, during more than a half of the observation the satellite was operating in the medium telemetry mode which led to telemetry saturation and resulted in data unusable for scientific analysis. During intervals when the high telemetry setting was utilized, the foreground illuminated XIS detectors (i.e., XIS 0, 2 and 3) operated in the 3 × 3 Event Editing mode with Burst Clock and 1/4 Window settings. The 3 × 3 Event Editing mode is not available for the XIS 1 for this observation. We therefore used data from XIS 0, 2, and 3 collected when high telemetry rate was utilized. We reduce the \textit{Suzaku} XIS and HXD data using the \texttt{xselect} and \texttt{xisresp} data analysis tool following the guidelines given by \textit{Suzaku} Data Analysis Guide. The XIS images indicate that a strong pile-up in the center of the source point-spread function (PSF) leads to a characteristic “crater.” In order to remove piled-up data we extracted XIS spectra from the annulus regions with the outer radius set to the maximum allowed by the XIS detector field of view (∼115 arcsec) and the inner radius was manually selected to excise the most piled up inner core of the PSF (∼15 arcsec). The spectra and corresponding responses were extracted by the \texttt{xselect} extractor and \texttt{xisresp}, \texttt{xismfgen} tools. Spectra and responses for individual detectors were then added using \texttt{mathpha} and \texttt{addmf} FTOOLS. We linearly rebin XIS spectral and response data to obtain 1024 spectral channels. The HXD/PIN spectrum was corrected for non-X-ray and cosmic X-ray backgrounds. We fit XIS and PIN spectra jointly in XSPEC using 0.7–9.0 keV energy range for XIS data and 15.0–40.0 keV range for PIN data fixing the cross-normalization factor between XIS and PIN spectra at unity. Due to large calibration uncertainties we also ignore 1.5–2.5 keV range for XIS spectrum.

For the continuum spectra we choose the sum of thermal (blackbody) and Comptonized (\texttt{comptt}; Titarchuk 1994) components, modified by interstellar photoelectric absorption according to Morrison & McCammon (1983). When we directly fit the data with this model we observe three distinct narrow features in the residuals (see Figure 1, left panel a). First, we see a line signature at 6–7 keV, which is the primary target of our investigation. We also observe a weak excess around 3.2 keV and a prominent line at 1 keV. The feature at 3.2 keV is probably an instrumental artifact. The line at 1 keV was reported previously from Cyg X-2 (Smale et al. 1993) and presumably belongs to the source spectrum. Both features are well represented by gaussian shape (see residuals on panel b of Figure 1). In addition to these narrow lines we observe a building-up excess toward higher energies in the XIS spectrum. This indicates a presence of a residual pile-up in the regions close to the excited central part of the PSF. To mitigate this effect we utilize the XSPEC \texttt{pileup} convolution model designed to model pile-up effect in CCD detectors. The XSPEC implementation of the pile-up model was initially designed to describe this effect in \textit{Chandra} data. However, the model, developed in Davis (2001), is valid for \textit{Suzaku} XIS detectors also. \textit{Suzaku} PSF of XIS CCDs is broader and spreads around larger number of pixels.

Figure 1. Left panel: identification of the continuum model and narrow lines in the \textit{Suzaku} spectrum of Cygnus X-2. Model residuals in units of 1σ error in corresponding channel are shown for (a) fit with continuum model \texttt{wabs(\texttt{comptt+bb})} only ($\chi^2_{\text{red}} = 7.5$), (b) fit with lines added at 1 keV and 3.2 keV \texttt{[wabs(\texttt{gaussian+gaussian+comptt+bb}), $\chi^2_{\text{red}} = 2.0$]}, (c) The pile-up model includes \texttt{[pileup+wabs(\texttt{gaussian+gaussian+comptt+bb})}}, $\chi^2_{\text{red}} = 1.7$. (d) Fit with energy range from 4.5 keV to 7.5 keV excluded and (e) the model obtained in (d) with channels between 4.5 keV and 7.5 keV noticed. Right panel: panel (d) on the right side zoomed in the iron line region. Emission line with an apparent red-skewness is seen in the data.

8 http://heasarc.gsfc.nasa.gov/docs/suzaku/aehp_data_analysis.html
pile-up was allowed to change which led to the best-fit value of the number of detector regions to consider independently for the morphing parameter, and 5% of the PSF to consider for pile-up. Finally, we excluded the energy range where the line profile is broad and red-skewed. In fact, the fit with the relativistic model (Model 4) produces the worst fit quality among the applied models but fits the spectrum with the relativistic and wind line models the standard set of XSPEC models and is implemented as a local model during our modeling. The windline model calculates the line profile by means of MC simulations. The input parameters of the model are the input line energy $E_L$, the depth of the wind $\tau_w$, the wind electron temperature $kT_w$, and the dimensionless wind speed $v/c$. The additional fixed parameter of the model is the number of individual photons $N_{ph}$ to be used in the MC simulation.

We did not observe any significant dependence of the $\chi^2$-statistic behavior on the number of photons used in our line simulations for $N_{ph}$ higher than $3 \times 10^4$. For the presented study we used $5 \times 10^4$ photons in the windline MC simulations. We summarize the results of our modeling and fit quality in Table 1. The resulting values of $\chi^2_{\text{red}}$ for Models 2, 3, and 4 are 1.31, 1.30, and 1.32, respectively. In Figure 2, we present the unfolded view of spectral fits with Model 4 where we used $5 \times 10^4$ photons in the MC simulation.

We also utilize the data from two RXTE observations made on 2006 July 25 and 2004 September 4 (Obs. IDs 92039-01-01-01 and 90030-01-39-00 correspondingly) to investigate the evolution of timing properties of Cyg X-2. We extract the RXTE/PCA energy spectra from Standard2 data modes and we use high-resolution modes to calculate power density spectra (PDS). We fit RXTE energy spectra in XSPEC with the model wabs(comptt+bbody+wline), where gaussian is used to model the iron line. The $N_H$ column density was fixed at $2.2 \times 10^{21}$. We obtain the following best-fit values. For ObsID 92039-01-01, comptt: $T_0 = 0.001$ keV
The presented evidence for the red-skewed iron line in Cyg X-2 along with the detection of the asymmetric lines in Serp X-1, 4U 1820–30, GX 349+2 (Bhattacharyya & Strohmayer 2007, C08), and 4U 1636–536 (Pundel et al. 2008), increases a number of NS showing this effect. This indicates that the red-skewed lines may be as abundant in NS sources as in BHs (e.g., Miller 2007). C08 interpreted these observed line appearances as the evidence of relativistic distortion due to the reflection from inner disk located close to the NS surface. The main argument in the association of the line skewness with the inner disk is that the highest observed kilohertz QPO in these sources is consistent with the Keplerian frequency at the inner disk radius predicted by the line profile.

The diskline model, when applied to the Suzaku (Model 2), leads to the best-fit value for the disk’s inner radius equal to the lower limit set by the model, i.e., $6 \, GM/c^2$, which formally translates into the radius of $\approx 12$ km for the NS mass of $1.4 \, M_\odot$. Model 3, which employs the laor component to represent the iron line, exhibits the same statistical performance as Model 2 and yields the radius of $9.5 \, R_G$ or 20 km. We should note that the laor model was formulated for the extreme Kerr BH case (see Laor 1991). In this model, the spin parameter $j = c J / GM^2$ was assumed to be close to unity. A moderately rotating accreting NS is expected to have a spin parameter less than 0.5. The NS spin in Cyg X-2 is not exactly known but if the difference between kHz QPO of $\sim 364$ Hz is taken as a spin estimate then the spacetime background near Cyg X-2 should satisfy Schwarzchild metric within 10% margin of error.

C08 found that their values of $R_{\text{in}}$ were consistent with the inner disk radius predicted by the beat-frequency model (Miller et al. 1998) from kHz QPO values. Maximum kHz QPO value observed in Cyg X-2 is 1007 kHz, which translates into 16.7 km radius if interpreted as a Keplerian frequency at the inner disk. This inferred radius is in between the $R_{\text{in}}$ values obtained using diskline and laor models. Interpretation of the highest kHz QPO peak as a Keplerian frequency is not unique. In the framework of the transition layer (TL) model the lower kHz QPO peak is classified as a Keplerian frequency (see Titarchuk 2002, and references therein). The TL model successfully describes the behavior of kHz QPOs in NS sources. The TL model QPO classification leads to the inner disk edge radius of 22.5 km. Beyond this radius the accreting gas enters the TL to adjust its motion to the rotation of the central star. While the value of the disk inner radius given by the TL model for the iron line can be considered to be in satisfactory agreement with the beat-frequency QPO model, it is harder to reconcile with the TL paradigm.

The red-skewed line-kHz QPO connection is based on the highest observed kHz QPO values (C08). However, the duty cycle of kHz QPOs is low. As noted by C08, the most compelling evidence for the inner disk origin of the line would come from the simultaneous observation of the kHz QPOs and the red-skewed iron line. At the time of this writing these two effects were not observed simultaneously from the same source.

The reason for absence of the simultaneous detection of kHz QPOs and broad iron line may be a lack of the correlated observation of high spectral resolution X-ray telescopes (i.e., Suzaku/ XMM-Newton) and RXTE. The Cyg X-2 Suzaku observation analyzed in this paper is a striking example how this lack of simultaneous coverage creates an obstacle in conducting scientific investigation. Namely, we have to search RXTE archive
for observation with similar spectral characteristics to estimate timing properties (see the previous section and the discussion below) while simultaneous RXTE data would allow to directly test timing properties more reliably.

A general idea about the fast timing properties can be inferred based on the archival RXTE data by matching the spectral parameters shown by RXTE instruments with those observed in the Suzaku spectrum in question. This approach is justified by the firmly established correlations between spectral characteristics and timing properties in NS LMXBs (Kaastra et al. 1998) and particularly in Cyg X-2 (Titarchuk et al. 2007). We searched RXTE archive for pointing observations nearest to 2006 May 16. Despite the fact that RXTE usually conducts frequent monitoring of Cyg X-2, we found that Suzaku observation was made in the middle of a 140 day gap in RXTE monitoring of this source. This, and the fact that Cyg X-2 is changing its state on a daily basis, does not permit us to test subsecond timing variability directly with RXTE. Therefore, we have to resort to search for matching spectral properties and rely on spectral-variability correlations.

We found that the nearest RXTE observation with the spectrum similar to the one shown by Suzaku was performed on 2004 September 4 (ObsID 90030-01-39-00, see the previous section). To compare this observation with the spectral state characterized by harder spectrum and lower opacity we arbitrarily choose the observation 92039-01-01-01 which is fit by compTT model with parameters $\tau_p = 12.6 \pm 0.4$ and $kT_e = 3.04 \pm 0.02$. In Figure 3 we show the energy and power spectra for these observations. It is clear that the variability for frequencies higher than 0.1 Hz is strongly suppressed and a “forest”-type PDS appears at frequencies above 0.1 Hz. The photon spectrum related to this PDS closely matches the Suzaku spectral data. This effect of variability suppression can be readily explained by a smearing of a signal in the opaque wind of optical depth $\tau_w$ because the suppression factor is related to the opacity in the wind as $\sim e^{-\tau_w}$. A higher gaussian equivalent width of 115 eV related to the 90030-01-39-00 RXTE observation with respect to that of 86 eV during the 92086-01-01-01 observation is another factor to support the low variability strong line connection.

The broadband variability continuum observed in PDS can be produced by diffusion of small disk perturbations propagating toward the central object. These disk perturbations result in a modulation of inner mass accretion rate, which then leads to variability in the X-ray flux (Lyubarskii 1997). Titarchuk et al. (2007) developed a theory of the diffusive propagation of perturbations in the disk and presented a model for the power spectrum formation. Application of the diffusion theory to the Fourier power spectra of Cyg X-2 and BH source Cyg X-1 led to the conclusion that the fast X-ray variability is produced in two configurations: in a large cold outer accretion disk and a compact geometrically thick configuration (i.e., transition layer). Long-term variations of the accretion matter supply at the outer accretion disk edge lead to changes of the source spectral state. Specifically, in high-boot state the innermost region becomes very compact and relatively cold as a result of the strong mass accretion. Presumably, this is the state which we are dealing with in the case of RXTE observation 90030-01-39-00 and the Suzaku observation. However, in this case, strong accretion disk presumably extended close to the central object should produce high-frequency perturbations leading to a broadband PDS continuum or kHz QPOs in the range $\sim 100$ Hz. None of these is seen in our data. This may be attributed to wind/outflow attenuation. It could present a problem for the relativistic disk reflection model of the iron emission-line production. We note, however, that the origin of fast variability and physical processes governing its evolution are not yet fully understood. Therefore, the above arguments does not provide a solid proof for the wind line model or a dismissal of the relativistic reflection scenario. Future studies on the asymmetric emission lines in X-ray binaries should address the above points using more substantial observational data. Observation of millisecond variability in the same data which would require wind opacities of 2–3 would provide grounds for the rejection of the wind model. Such cases have not been observed yet. On the other hand, further evidence of the correlation of “forest”-type PDS with the asymmetric line would rule out relativistic reflection paradigm.

Cyg X-2 is a Z source (Hasinger & van der Klis 1989) and presumably accretes at a rate close to the Eddington limit. Therefore, strong outflows are expected in this source, naturally leading to the production of the red wing of the iron line in this wind/outflow configuration. This hypothesis is supported by the fact that Z sources have strong radio counterparts. Paizis et al. (2006) analysis of radio/X-ray correlation in Z and bright atoll sources that radio and Comptonized emission in these sources originate in same optically thick plasma with the temperature 2.5–3 keV near NS. Moreover, strong requirement for the disk illumination to be concentrated very close to its inner edge (Nandra et al. 1999) in the relativistic line formation scenario led Reynolds & Begelman (1997) to consider the production of fluorescent emission within the innermost stable orbit region where matter spirals into the compact object. However, as indicated by the models of Nayakshin et al. (2000) and Ballantyne et al. (2001), the ionization of such a disk by the intense X-ray radiation might further invalidate some of basic assumptions associated with this interpretation. These arguments indicate that the wind/outflow paradigm may indeed be at work as (or at least contribute to) an origin of the red skewness in the iron lines in compact sources.

4. CONCLUSIONS

We present the analysis of the Suzaku spectrum from NS Cyg X-2. We discover a $K_{\alpha}$ iron line which shows significant red wing. This is the fifth NS source so far to show asymmetric line profile. We analyze the line in terms of the relativistic emission from the inner accretion disk and in terms of the wind-outflow model.

We conclude that both models are acceptable according to the statistical performance. However, the wind model appears to give more adequate explanation which does not require the accretion disk inner edge to advance close to NS surface. We also consider the line production scenarios in the context of the timing properties. We identify RXTE observation which shows spectrum very similar to that during Suzaku observation which shows the red-skewed line. These RXTE data indicate that the source fast variability is strongly suppressed, which can be attributed to smearing in a strong wind. This lack of high frequency variability weakens the red-skewed line connection with kHz QPO and strengthens its connection to a wind/outflow phenomena.

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