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Suzaku observations of Fe Kα line in some hard X-ray emitting symbiotic stars and magnetic cataclysmic variables

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Abstract. We present the Suzaku observations of Fe Kα for four Hard X-ray emitting symbiotic stars (hSSs) and 19 magnetic cataclysmic variables (mCVs). The 6.7 and 7.0 keV emission lines are typically created by collisional excitation in the vicinity of the white dwarf arising from the shock front. The 6.4 keV iron emission line in contrast is formed in equilibrium by irradiation of the neutral (or low ionized) iron by a hard X-ray source, as a collisional origin would lead to rapid ionization. We have surveyed the emission using a collection of Suzaku observations of hSSs and mCVs to better understand the geometry of these systems. We find that they do not seem to have a single geometry, and that while absorption-induced fluorescence leads to some emission in three hSSs and 12 mCVS, there are strong hints that significant 6.4 keV emission arises in the accretion disk irradiated by the hard X-rays from the boundary layer between the accretion disk and hot white dwarf, in the case of hSSs (SS73 17). For mCVs, the 6.4 keV line emission arises from the reflection of hard X-rays from the white dwarf surfaces in 5 mCVs. This suggests there could be relevant information about the geometry of the WD in the system encoded in the Fe Kα line.

Key words. Stars: hard X-rays – emission lines

1. Introduction

Symbiotic stars are interacting binaries formed by a red giant star and a hot degenerate companion which accretes mass from the stellar wind of the red giant, forming a nebula surrounding the system which is typically detected via various optical emission lines. Detailed properties of hard X-ray emitting symbiotic stars are given by Eze (2011), and references therein. Magnetic Cataclysmic Variables (mCVs) on the other hand are interacting binaries formed by a magnetic white dwarf and a low-mass main sequence star. Matter flowing from the Roche Lobe filled main-sequence star is magnetically funnelled onto the magnetic poles of the white dwarf (WD), resulting in accretion of matter at the poles. The accretion flow is usually highly supersonic as it approaches the white dwarf producing a strong steady shock close to the white dwarf surface, hence turning the accreting matter into hot plasma with T $\sim 10^8$ K at the shock front, which radiates hard X-rays (Ezuka & Ishida 1999). There are two types of mCVs, the polars (AM Herculis type) which are characterized by a strong magnetic field and intermediate polars (DQ Herculis systems) with a weaker magnetic field. The production of hard X-ray in mCVs is by the magnetically channelled accretion column, whose impact on the WD poles is followed by thermal bremsstrahlung cooling by free electrons with kT of the order of 10 keV and above (Cropper 1990; Warner 2003). The emission is assumed to be through the post-shock region, which is below the shock front created from the impacting accretion column. The observed soft X-rays from mCVs are created from the absorption and reprocessing of the hard X-rays in the plasma close to the surface of the WD.

Hard X-ray emitting symbiotic stars (hereafter hSSs) such as CH Cyg, T CrB, RT Cru and SS73 17 observed with Suzaku satellite were found to emit strong Fe Kα fluorescence emission line at 6.4 keV with an average equivalent width of 180 eV and the 6.7 and 7.0 keV lines with equivalent width of 88 and 74 eV respectively (Eze et al. 2012).

The mCVs have also been observed to emit Fe Kα lines, which can be resolved into fluorescence (6.4 keV) and He-like (6.7 keV) and H-like (7.0 keV) lines (Ezuka & Ishida 1999; Mukai et al. 2003; Hellier & Mukai 2004; Yuasa et al. 2010). Ezuka & Ishida (1999) also suggested that the reflection from the white dwarf surface makes a significant contribution to the observed Fe Kα fluorescence line. However, the origin of these lines in mCVs is yet to be completely addressed. The 6.4 keV iron emission line is typically created by irradiation of the neutral (or low ionized) material (iron) by a hard X-ray source. Eze (2014a) discussed in detail previous observations of the Fe Kα line in Seyfert galaxies, AGN, quasars and other galaxies.

The Fe Kα line of the mCVs has been observed to be similar to, and contributes to, the Fe Kα line of the Galactic X-ray emission (GRXE, Bleach et al. 1972; Worrall et al. 1982; Iwan et al. 1982; Ebisawa et al. 2001; Tanaka 2002; Revnivtsev & Sazonov 2007). This makes the study of the Fe Kα line of the mCVs significant beyond simply providing a better understanding of these systems themselves. Also the Fe Kα line of the hSSs has been observed to be similar and contributes to Fe Kα line of the Galactic X-ray emission (see Eze et al. 2012).

The question this work will address is what are the origin of these emission lines? In order to answer this question we carried out spectral re-analysis of the Suzaku observations on these systems and our result supports the earlier results that the possible origin of the hard X-rays emitted from the hSSs is from the boundary layers between the accretion disk and accreting white dwarf (Luna & Sokoloski 2007; Eze et al. 2010).

We present here the Suzaku observations of Fe Kα line of four hSSs and 19 mCVs and discuss the possible origin of the components of this line. We discuss data selection in section 2, Data analysis and results in 3, and in 4 we discuss our result and conclusions.

2. Data selection

The hSSs and mCVs were selected based on the fact that they have been observed with Suzaku and were confirmed to have strong Fe Kα emission lines with hard-tails above 20 keV. Four hard X-ray emitting symbiotic stars, SS73 17, RT Cru, T CrB, and CH Cyg (e.g., Kennea et al. 2009; Eze et al. 2010) were selected and used for our study (Table 1). In selecting the mCVs, we used a CV catalog (Ritter & Kolb 2003) and the intermediate polar (IP) catalog[1]. Five sources in the catalog, AE Aqr, AM Her, GK Per, 1RXS J070407.9+26250, and 1RXS J180340.0+40121 were dropped, even though observed with Suzaku, because they appear to had been too faint during their observations or have perculiar emission mechanism (AE Aqr: e.g., Wynn et al. 1997). A total of 19 sources were thus selected (Table 1).

3. Data analysis and results

Analysis of our data was done using version 2 of the standard Suzaku pipeline products, and the HEASoft[2] version 6.10.

[1] `http://asd.gsfc.nasa.gov/Koji.Mukai/iphome/catalog/alpha.html`

[2] See `http://heasarc.gsfc.nasa.gov/lheasoft/` for details.

Spectral analyses of all observations were performed using XSPEC version 12.7. We modeled the spectrum using absorbed bremsstralung model with three Gaussian lines for the three Fe Kα emission lines to measure the iron line fluxes. We assumed two types of absorption by full-covering and partial covering matter. Since we were primarily interested in the ion lines, our fitting covers 3–10 keV for the XIS BI, 3–12 keV for the XIS FI and 15–40 keV for the HXD PIN. We ignored energy range below 3 keV in the XIS FI and BI detector to avoid intrinsic absorption which is known to affect data at this energy range, and energies above 10 keV were ignored for XIS BI because the instrument background is higher compared to the XIS FI detectors. We also ignored energy range above 40 keV in the HXD PIN detector in order to obtain high signal-to-noise ratio signals.

The three Fe lines, neutral or low ionized (6.4 keV), He-like (6.7 keV), and H-like (7.0 keV) ions, were clearly resolved in all the sources except IGR J17303–0601 where we were unable to detect the H-like (7.0 keV) significantly but the other two lines were detected. Spectra of all the sources were published in Eze (2014a,b) and spectral parameters were shown in Table 1.

We confirmed the presence of reflection component in some of our sources by modeling with an absorbed bremsstrahlung plus a reflection component (see Eze 2014a,b).

4. Discussion and conclusion

4.1. On the origin of hard X-rays and the 6.4 keV line from hSSs and mCVs

Symbiotic stars are generally known to emit soft X-rays, which are believed to result from materials burning quasi-steadily on the white dwarf WD surface (Jordan et al. 1994; Orio et al. 1961). A small class of symbiotic stars emit hard X-rays, SS73 17, RT Cru, CH Cyg, T CrB, and MWC 560. The origin of hard X-rays from hSSs had been addressed by some authors (Luna & Sokoloski 2007; Kennea et al. 2009; Eze et al. 2010) which points to the boundary layer between the accreting white dwarf and the accretion disk. This seems most likely since no other area or mechanism in the system can produce such high energy X-rays. Other possible sources, such as magnetic reconnection in the base of jet or an expanding shock front are not likely to be present in a white dwarf / red giant system. The detection of strong iron lines and most particularly the thermal bremsstrahlung continuum with an average temperature of 20 keV in all the sources strongly supports the thermal origin of the hard X-rays, and in particular the collisional origin of the He-like and H-like 6.7 and 7.1 keV lines. Hence, these hard X-rays are most likely released during the accretion process as material from the red giant companion falls down towards the white dwarf and stops at the boundary layer. We note as further evidence for this picture that we observed high absorption of the hard X-rays with both full covering and partial covering in all the sources (see Table 1), consistent with a large accretion column covering the hot interaction region.

Hard X-rays observed in mCVs with modern hard X-ray telescopes like the *INTEGRAL*/IBIS, *SWIFT*/BAT and *SUZAKU*/HXD show that in most cases IPs are found to produce about 10 times more hard X-rays than polars due to their higher mass transfer rate and intrinsically harder spectrum (Warner 2003). Our sources have spectra that are well fit with a thermal model (see Ezuka & Ishida 1999) signifying that the hard X-rays in mCVs are likely thermal in origin. We, therefore, confirm that the hard X-rays from these mCVs originate from the shock front close to the white dwarf magnetic poles due to bremstrahlung cooling by free electrons with average temperature of 18 keV as was earlier observed by Cropper (1990); Warner (2003).

The 6.4 keV fluorescence line emission is usually caused by irradiation of (near-) neutral material (in this case, iron) by a hard X-ray source, ejecting one of the 2 K-shell (n = 1) electrons of an Fe atom (or ion). While electron collisions could also cause such an ejection, and in hSSs a $\sim$ 20 keV collisional plasma is often seen, this is unlikely to be the origin as a collisional plasma would rapidly ionize the iron. The more likely scenario is that there is

Table 1. The Fe lines fit parameters.

Source Name	N_H^f	N_H^p	C	kT	F_{cont}	$E_{6.4}$	$F_{6.4}$	$EW_{6.4}$	$E_{6.7}$	$F_{6.7}$	$EW_{6.7}$	$E_{7.0}$	$F_{7.0}$	$EW_{7.0}$
Symbiotic Stars														
CH Cyg	22.0 ± 7.0	99^{+26}_{-37}	0.91 ± 0.04	6^{+3}_{-2}	9.2 ± 0.5	6.41 ± 0.02	20.2 ± 0.6	580^{+424}_{-65}	6.59 ± 0.05	5.9 ± 1.8	111^{+95}_{-35}	$6.81^{+0.12}_{-0.07}$	1.8 ± 0.7	66^{+87}_{-38}
T CrB	17.7 ± 2.2	37 ± 6	0.71 ± 0.06	19^{+3}_{-2}	14.7 ± 1.3	6.43 ± 0.01	9.6 ± 0.6	117^{+48}_{-46}	6.72 ± 0.02	6.5 ± 0.5	85^{+40}_{-12}	7.01 ± 0.02	5.3 ± 0.3	104^{+38}_{-41}
RT Cru	3.3 ± 0.4	58 ± 9	0.46 ± 0.05	29^{+9}_{-5}	12.0 ± 1.1	6.38 ± 0.01	11.0 ± 0.9	174^{+38}_{-30}	6.64 ± 0.01	5.8 ± 0.5	52^{+34}_{-15}	6.96 ± 0.01	3.2 ± 0.3	51^{+17}_{-25}
SS73 17	9.2 ± 0.5	34 ± 5	0.65 ± 0.05	38 ± 6	4.9 ± 1.0	6.38 ± 0.01	7.6 ± 0.6	185^{+120}_{-63}	6.67 ± 0.01	7.7 ± 0.2	158^{+136}_{-41}	6.95 ± 0.01	4.4 ± 0.1	93^{+116}_{-40}
Polars														
V1432 Aql	3.0 ± 0.5	61 ± 9	0.56 ± 0.05	15 ± 3	$14.7^{+3.8}_{-2.9}$	6.42 ± 0.01	6.5 ± 0.7	91^{+33}_{-20}	6.67 ± 0.02	5.5 ± 0.5	84^{+40}_{-8}	7.00 ± 0.03	2.0 ± 0.4	42^{+29}_{-34}
Intermediate Polars														
NY Lup	0.6 ± 0.5	32 ± 8	0.35 ± 0.03	40 ± 7	$9.6^{+0.5}_{-0.3}$	6.40 ± 0.01	7.1 ± 0.3	118^{+34}_{-12}	6.66 ± 0.01	5.9 ± 0.3	94^{+43}_{-9}	6.94 ± 0.01	4.7 ± 0.2	70^{+28}_{-17}
RX J2133.7+5107	2.3 ± 0.3	73 ± 10	0.46 ± 0.05	29^{+10}_{-6}	8.9 ± 0.9	6.42 ± 0.01	6.3 ± 0.5	147^{+46}_{-26}	6.68 ± 0.02	3.1 ± 0.3	52^{+32}_{-14}	6.98 ± 0.02	2.3 ± 0.3	57^{+16}_{-26}
EX Hya	—	—	—	10 ± 1	20.8 ± 0.1	6.41 ± 0.01	3.3 ± 0.2	28 ± 3	6.66 ± 0.02	2.9 ± 0.3	32 ± 1	6.95 ± 0.01	1.1 ± 0.3	109^{+5}_{-4}
V1223 Sgr	2.3 ± 0.2	72 ± 5	0.41 ± 0.03	25 ± 3	34.5 ± 0.3	6.38 ± 0.01	15.7 ± 0.7	89^{+17}_{-8}	6.67 ± 0.01	11.3 ± 0.6	59^{+18}_{-8}	6.95 ± 0.01	8.3 ± 0.5	45^{+14}_{-12}
MU Cam	1.8 ± 1.3	35 ± 14	0.48 ± 0.06	29^{+14}_{-8}	$3.6^{+0.8}_{-0.4}$	6.41 ± 0.01	2.9 ± 0.3	160^{+70}_{-32}	6.68 ± 0.02	2.5 ± 0.2	104^{+71}_{-22}	6.98 ± 0.01	2.4 ± 0.2	102^{+58}_{-36}
V2400 Oph	1.4 ± 0.2	64 ± 7	0.36 ± 0.04	18 ± 2	16.8 ± 0.3	6.39 ± 0.01	9.7 ± 0.5	112^{+26}_{-10}	6.68 ± 0.01	7.1 ± 0.3	77^{+24}_{-7}	6.96 ± 0.01	4.7 ± 0.3	57^{+20}_{-13}
YY Dra	—	—	—	17 ± 1	8.2 ± 0.1	6.41 ± 0.02	2.2 ± 0.3	49^{+34}_{-22}	6.69 ± 0.01	6.6 ± 0.4	157^{+52}_{-19}	6.99 ± 0.02	4.4 ± 0.4	173^{+63}_{-92}
TV Col	4.1 ± 0.2	—	—	27 ± 2	13.6 ± 1.2	6.41 ± 0.01	8.7 ± 0.3	114^{+39}_{-12}	6.69 ± 0.02	9.7 ± 0.2	122^{+45}_{-11}	6.98 ± 0.01	6.7 ± 0.1	99^{+41}_{-21}
V709 Cas	0.5 ± 0.4	51 ± 18	0.26 ± 0.07	26^{+7}_{-5}	$11.2^{+2.0}_{-1.3}$	6.41 ± 0.02	6.3 ± 0.5	108^{+33}_{-18}	6.69 ± 0.02	2.8 ± 0.4	56^{+29}_{-15}	6.99 ± 0.02	2.8 ± 0.3	48^{+27}_{-24}
IGR J17303−0601	1.9 ± 0.7	106^{+25}_{-28}	$0.56^{+0.09}_{-0.12}$	29 ± 7	10.5 ± 1.7	6.39 ± 0.02	4.6 ± 0.7	89^{+20}_{-16}	6.67 ± 0.04	2.3 ± 0.5	45^{+18}_{-13}	—	—	—
IGR J17195−4100	—	21^{+8}_{-5}	0.27 ± 0.02	26 ± 5	$9.6^{+0.2}_{-0.5}$	6.40 ± 0.01	5.9 ± 0.4	113^{+40}_{-20}	6.69 ± 0.01	4.9 ± 0.4	90^{+39}_{-17}	6.97 ± 0.02	4.0 ± 0.4	82^{+40}_{-26}
BG CMi	$5.4^{+2.9}_{-1.0}$	43 ± 24	0.39 ± 0.09	19^{+5}_{-4}	$8.8^{+2.7}_{-1.4}$	6.40 ± 0.02	3.6 ± 0.4	86^{+17}_{-15}	6.65 ± 0.03	2.4 ± 0.3	57^{+23}_{-14}	7.00 ± 0.04	1.3 ± 0.3	39^{+23}_{-14}
PQ Gem	2.0 ± 0.4	64 ± 13	0.46 ± 0.07	18 ± 6	7.7 ± 0.2	6.39 ± 0.01	5.0 ± 0.6	137^{+28}_{-39}	6.66 ± 0.03	1.7 ± 0.4	32^{+60}_{-25}	6.93 ± 0.04	1.1 ± 0.4	23^{+37}_{-23}
TX Col	1.8 ± 0.6	59 ± 16	0.50 ± 0.08	12^{+4}_{-3}	$5.2^{+0.3}_{-0.1}$	6.38 ± 0.02	1.6 ± 0.3	47^{+51}_{-33}	6.68 ± 0.02	2.4 ± 0.3	83^{+71}_{-30}	6.95 ± 0.02	1.6 ± 0.2	49^{+52}_{-36}
FO Aqr	10.2 ± 0.2	—	—	27 ± 2	37.0 ± 1.0	6.37 ± 0.01	28.4 ± 1.0	149^{+39}_{-30}	6.65 ± 0.01	16.6 ± 1.0	80^{+33}_{-54}	6.92 ± 0.02	11.1 ± 1.0	49^{+26}_{-22}
AO Psc	4.2 ± 0.2	40 ± 5	0.57 ± 0.06	17 ± 1	$13.8^{+0.8}_{-0.1}$	6.37 ± 0.01	8.9 ± 0.3	91^{+38}_{-16}	6.66 ± 0.02	13.0 ± 0.2	136^{+47}_{-16}	6.94 ± 0.01	7.4 ± 0.2	59^{+24}_{-21}
IGR J00234+6141	0.4 ± 0.5	32 ± 6	0.30 ± 0.04	24 ± 7.2	$2.1^{+1.6}_{-0.4}$	6.40 ± 0.03	1.2 ± 0.2	111^{+87}_{-39}	6.65 ± 0.04	6.2 ± 0.1	49^{+102}_{-36}	6.97 ± 0.03	0.6 ± 0.1	60^{+97}_{-43}
XY Ari	6.9 ± 0.2	26 ± 4	0.49 ± 0.05	28 ± 4	5.1 ± 0.6	6.39 ± 0.01	2.5 ± 0.7	85^{+32}_{-15}	6.68 ± 0.01	3.1 ± 0.3	112^{+33}_{-12}	6.97 ± 0.01	1.7 ± 0.4	72^{+31}_{-17}
Average Spectra														
Average hSSs	5.6 ± 0.2	50 ± 2	0.70 ± 0.01	20 ± 1	10.7 ± 1.3	$6.408^{+0.002}_{-0.005}$	7.7 ± 0.7	179^{+46}_{-11}	6.671 ± 0.007	5.2 ± 0.3	88^{+43}_{-8}	$6.969^{+0.013}_{-0.008}$	3.8 ± 0.3	74^{+28}_{-17}
Average mCVs	1.6 ± 0.1	66 ± 1	0.44 ± 0.01	18 ± 1	12.3 ± 0.4	$6.403^{+0.003}_{-0.001}$	5.8 ± 0.1	93^{+20}_{-3}	$6.671^{+0.001}_{-0.002}$	7.7 ± 0.1	114^{+11}_{-4}	$6.957^{+0.003}_{-0.002}$	4.2 ± 0.1	62^{+7}_{-4}

Parameters are the hydrogen column density of the full-covering and the partial-covering matter in units of 10^{22} cm^{-2} (N_H^f and N_H^p), the covering fraction of the partial-covering matter (C), the continuum temperature in keV (kT), the continuum flux in 10^{-3} photons s^{-1} cm^{-2} (F_{cont}), the center energies of 6.4, 6.7, and 7.0 keV lines in keV ($E_{6.4}$, $E_{6.7}$, and $E_{7.0}$), the line fluxes in 10^{-5} photons s^{-1} cm^{-2} ($F_{6.4}$, $F_{6.7}$, and $F_{7.0}$), and the equivalent widths in eV ($EW_{6.4}$, $EW_{6.7}$, and $EW_{7.0}$). EX Hya and YY Dra do not have both absorptions (N_H^f and N_H^p), IGR J17195−4100 has no N_H^f, while TV Col and FO Aqr have no N_H^p.

some separation between the energetic X-ray photon-emitting plasma and the (near-) neutral Fe atoms.

4.2. Case I: the accretion disk / reflection origin

Hard X-rays from the boundary layers between the accretion disk and the compact objects (see e.g. Luna & Sokoloski 2007; Eze et al. 2010) irradiate the cold gas in the accretion disk leading to the emission of the Fe Kα fluorescence line in hSSs. In the case of hSSs that accrete matter directly from the wind of the red giant, hard X-rays released from the surface of the white dwarf during the accretion of matter, irradiates matter in the thick cold gas surrounding the white dwarf thereby emitting the 6.4 keV line.

We detected significant reflection of hard X-rays from the white dwarf surfaces of five out of our 19 sources from modeling our sources with the XSPEC reflect model in addition to an absorbed bremsstrahlung model. This indicates that hard X-rays from the shock front or the boundary layers between the accretion disk and the compact objects (see e.g. Luna & Sokoloski 2007; Eze et al. 2010; Eze 2014a) irradiate the cold gas of at least half of the surface of the accretion disk of FO Aqr and a significant fraction of the accretion disks of AO Psc, V1223 Sgr, V240 Oph and RX J2133.7+5107, leading to the emission of the Fe Kα fluorescence line (see Eze 2014b). However, the remaining 14 sources have low or no reflection of hard X-rays from their accretion disk. These sources have absorption column densities of the order of $N_{\rm H} \sim 10^{23}$ cm^{-2} for the partial–covering matter except for EX Hya and YY Dra in which we did not detect either the full covering and partial covering absorption. Also TV Col and FO Aqr have no partial covering absorption, while IGR J17105–4100 has no full covering absorption (see Table 1). We will discuss the mechanism for the creation of the Fe Kα fluorescence line in such system with absorption column densities of the order of $N_{\rm H} \sim 10^{23}$ cm^{-2} for both the full–covering and partial–covering in the next section.

4.3. Case II: the cold absorber option

Hard X-rays traveling through absorbing material will interact with the iron, just as in the reflection case, to create Fe Kα fluorescence lines. In this case, the fluorescence iron line intensity will increase with the thickness $N_{\rm H}$ of the ambient matter. Of course, when $N_{\rm H}$ becomes larger than (3–5) $\times$ 10^{23} cm^{-2}, the line intensity starts to decrease due to self-absorption of photons by the matter (Matsuoka et al. 1986). Iron Kα lines which were observed in a few AGN that showed absorption column densities of $N_{\rm H}$ ~ 10^{23} cm^{-2} such as Centaurus A (Mushotzky et al. 1978) and NGC 4151 (Perola,G.C., et al. 1986) has been linked to the fluorescence from the same matter in the absorption column (Piro et al. 1993).

The large absorption column density of the order of 10^{23} cm^{-2} in hSSs and some mCVs guarantees that some of the iron fluorescent line will arise from interactions between the hard X-rays with the thick column density of cold matter in our line of sight (see e.g. Matsuoka et al. 1990). This picture is enhanced by a review of Table 1, which shows that the largest Fe Kα EW of 580^{+424}_{-65} eV, seen in CH Cyg, is also associated with the largest actual column density, using either the observed full-covering value or the sum of the total and the weighted partial covering fraction as a proxy for the $N_{\rm H}$. Piro et al. (1993) found that the EW generated by passage through optically-thin absorbing material is ~ 100eV $\times A_{Fe} \times {\rm N}_{\rm H}^{23} \times f_{\Omega}$, where A_{Fe} is the Fe abundance to solar, ${\rm N}_{\rm H}^{23}$ is the column density in units of 10^{23} cm^{-2} and f_{Ω} is the total covering fraction of the absorber. In the case of CH Cyg for example, this would create an EW of either 220 eV (using only the full fraction) or 1120 eV using the weighted value.

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