Fe Kα Line in Hard X-ray Emitting Symbiotic Stars

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ABSTRACT

The 6.4 keV iron emission line is typically created by irradiation of the neutral (or low ionized) iron by a hard X-ray source. Whereas the 6.7 and 7.0 keV emission lines are mainly produced by photoionization and collisional excitation in hot plasma, the 6.4 keV fluorescence line is typically a signature of either reflection from an accretion disk or absorption. We have surveyed the emission using a collection of Suzaku observations of hard X-ray emitting symbiotic stars 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 of the hard X-ray emitting symbiotic stars (hSSs) in our study, CH Cyg, T CrB and RT Cru 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 one of our sources, SS73 17. The 6.7 and 7.0 keV lines, however, are largely produced by collisional excitation in the vicinity of the compact white dwarf.

Key words: X-rays:stars (stars:) binaries: symbiotic

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.

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. This line was first discovered in an astronomical context by Mushotzky et al. (1978) in OSO-8 X-ray observations of Cen A (NGC 5128). NGC 5128 is one of the closest radio galaxies and one of the first extragalactic objects to be identified as an X-ray source. X-ray binaries also showed K-shell transitions from cold neutral metals (e.g. Basko (1978)). The Ginga satellite also detected a strong Fe Kα fluorescence line in a number of Seyfert 1 galaxies (see e.g. Kinkhabwala et al. (2003); Matsuoka et al. (1990); Piro et al. (1990); Pounds et al. (1990)). The Fe Kα line of active galactic nuclei, as well as different geometries and astrophysical conditions necessary for its emergence, was intensively studied in the 1990s (see e.g. Matt et al. (1986); George & Fabian (1991)).

The key results of these studies was that the fluorescent Fe Kα at 6.4 keV originates from the innermost part of accretion disk, close to the central compact object. The general consensus is that X-ray irradiation of the surface layers of the accretion disk in radio galaxies and AGN, especially Seyfert galaxies gives rise to fluorescent Fe Kα emission line. As an extreme example, Ballantyne & Fabian (2005) discovered a broad Fe Kα line emitted from a region which had inner radius close to the innermost stable circular orbit ($R_{\text{ms}}$) for a maximally spinning black hole with outer radius within 10 $R_g$ (where $R_g$ is the gravitational radius) using XMM-Newton observation of the broad-line radio galaxy 4C 74.26. The Fe Kα fluorescence line is typically strong, thanks to iron’s high abundance and the large radiative transition rate for the 2p–1s transition. It can be found in the spectra of all types of accreting sources: binary black hole and neutron star systems, cataclysmic variable stars, hard X-ray emitting symbiotic stars and AGN.

The ASCA satellite with its excellent spectral resolution and sensitivity, was used to obtain the first convincing proof for the existence of a relativistically broadened Fe Kα fluorescence line in the spectra of Seyfert 1 galaxy MCG-6-30-15 (Tanaka et al. 1995). Similar studies had been performed on samples of local AGN (see e.g. Nandra et al. (1997); Yaqoob et al. (2003); Nandra et al. (2007); Markowitz et al. (2008), and some distant quasars (Corral et al. 2008) leading to the understanding of the properties of the Fe Kα fluorescence line emission.
The 6.7 and 7.0 keV emission lines, in contrast, are produced by either photoionization or collisional excitation in hot plasma, depending upon the source. In AGN and black hole binaries these lines are largely produced by photoionization due to intense X-ray luminosity from the compact objects, while in neutron stars and white dwarf binaries collisional processes from the accretion process can dominate.

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 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 conclusions on these systems and our result supports the earlier conclusions.

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The hSSs 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).

2 DATA SELECTION

The hSSs 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).

3 DATA ANALYSIS AND RESULTS

Analysis of our data were done using version 2 of the standard Suzaku pipeline products, and the HEASoft version 6.10. In majority of the sources we used 250″ radius to extract all events for the XIS detector for the production of the source spectra but in some cases where the 250″ radius overlaps with the calibration sources at the corners, we adjusted the radius accordingly. The XIS background spectra were extracted with 250″ radius with no apparent sources and were offset from both the source and corner calibrations. The radius was also adjusted accordingly in some cases where it overlaps with the calibration sources at the corners.

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The three lines, from (near-) neutral (6.4 keV), He-like (6.7 keV), and H-like (7.0 keV) iron ions were clearly resolved in all the sources. Spectra of all the sources were presented in Figure 1 and spectral parameters were shown in Table 3.

We detected strong 6.4 keV iron line emission in all the hSSs spectrum with an average equivalent width (EW) of 221 eV and strong 6.7 and 7.0 keV lines with average equivalent width of 92 and 75 eV, respectively.

The values of the reduced $\chi^2$ for the absorbed bremsstrahlung, power law plus XSPEC reflect model and absorber bremsstrahlung plus XSPEC reflect models were presented in Table 2. Our modeling of the spectrum of our sources with power law plus XSPEC reflect model with three Gaussian lines for the iron lines did not produce a statistically acceptable fit. This is not surprising since our knowledge of hard X-ray emitting symbiotic stars shows that we always require a thermal model to obtain a statistically acceptable fit at the lower energy band (0.1–10 keV) (see Enzaki et al. (1998); Luna & Sokoloski (2005); Smith et al. (2008); Kennea et al. (2009); Eze et al. (2010)). However, at higher energy bands (15–500 keV) a non-thermal spectrum can be detected in some sources. As an example the INTEGRAL observations of RT Cru were well fit with nonthermal power law emission with photon index $\Gamma = 2.7$ (Chernyakova et al. 2005). This implies that non-thermal radiation mechanism could possibly be present in our sources, but is not apparent except at the higher energy band. We confirmed the presence of reflection component in one of our sources SS73 17, from modeling our sources with an absorbed bremsstrahlung plus XSPEC reflect model (see Table 2 for the reduced $\chi^2$ values).
4 DISCUSSION AND CONCLUSION

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

Symbiotic stars are generally known to emit soft X-rays, which are believed to be resulting 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 3), consistent with a large accretion column covering the hot interaction region.

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 ~20 keV collisional plasma is often seen, this is unlikely to be origin as a collisional plasma would rapidly ionize the iron. The more likely scenario is that there is some separation between the energetic X-ray photon-emitting plasma and the (near-) neutral Fe atoms.

One K-shell electron is ejected following photoelectric absorption of a hard X-ray, the resulting excited state can decay in one of two ways. An L-shell (n = 2) electron may drop into the K-shell releasing ~6.4 keV of energy either as a fluorescence emission line photon or an Auger electron. An Auger electron occurs when the energy produced by the n = 2 → n = 1 transition is internally absorbed by another electron which is ejected from the ion.). The ~6.4 keV line is actually a doublet, with slightly different energies depending on spin-orbit interaction energy between the electron spin and the orbital momentum of the 2p orbital. These two line components of the Kα line are at 6.404 and 6.391 keV, though they are not separately distinguished at CCD resolution. The hSSs are binary systems, with a white dwarf accreting matter from an accretion disk, though some hSSs are believed to have a white dwarf accreting matter from a cocoon of gas surrounding it and coming from the red giant companion (see e.g. Sokoloski et al. 2001; Zamanov et al. 2010).

4.2 Case I: The Accretion Disk / Reflection Origin

The result of modeling our sources with addition of the XSPEC reflect model to an absorbed bremsstrahlung shows that there is none or low reflection of hard X-rays in CH Cyg, T CrB and RT Cru, while for SS73 17 there is significant indication that 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 at least half of the surface of the accretion disk leading to the emission of the Fe Kα fluorescence line (see Table 2). Interestingly two of our sources CH Cyg and T CrB has absorption column densities of the order of $N_H \sim 10^{23} \text{cm}^{-2}$ in both full-covering and partial-covering matter, while for RT-Cru the absorption column densities is of the order of $N_H \sim 10^{22} \text{cm}^{-2}$ for the full-covering matter and it is in $N_H \sim 10^{23} \text{cm}^{-2}$ for the partial-covering matter (see Table 3). The mechanism for the creation of the Fe Kα fluorescence line in such system will be discussed in the next section. 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.

Generally, for some compact objects that accrete matter through the accretion disk process such as the white dwarfs, neutron stars, and black holes, there are always the emission of Fe Kα fluorescence line as well as Compton reflection, both signifying the presence of cold matter. Fe Kα fluorescence lines were detected in Seyfert galaxies with typical EW of ~200-300 eV using ASCA (Nandra et al. 1997, 2007). Compton reflection was earlier discovered also in Seyfert galaxies by Ginga (Matsuoka et al. 1994; Piro et al. 1994; Pounds et al. 1990) and the average solid angle $\Omega$ subtended by the reflecting medium was $\Omega/2\pi = 0.5$ (Nandra et al. 1997). The range of possible EW depends upon the geometry of the source. If the ionizing source itself is not hidden from view, then the largest possible EW is ~200 eV (George & Fabian 1991) for a face-on slab of material with typical iron abundances. This value can be exceeded if the source is hidden from view by an optically thick absorber and only the reflected light observed, but such a situation is more likely to occur in an AGN with a large surrounding torus than in a hSS with only the accreted matter from red giant wind to provide absorption. We note that three of our four sources all have 6.4 keV EW’s under 200 eV (see Table 3), although this is only corroborating evidence for the reflection / accretion disk geometry picture.

Compton reflection plays a vital role in the X-ray spectrum of many compact objects especially in active galactic nuclei (AGN) and black hole candidates (BHC) sources. When the primary X-rays hits Thomson-thick matter (e.g. the accretion disk), Compton-scattered X-rays enter into our line of sight. Elements like iron, which are in low state of ionization, can absorb the lower energy X-rays and so flatten the reflection continuum leading to the production of the fluorescent line emission (Matt et al. 1986; George & Fabian 1991). In most AGN such as Seyfert 1 galaxies, the basic spectral model is that of a hard X-ray emitting continuum source illuminating an accretion disk, which leads to the observed reflected hard X-ray emission together with
soft X-rays from thermal emission disk. However in some AGN sources (e.g. Kunieda et al. (1987); Day et al. (1990); Piro et al. (1990)), with large iron line equivalent width of the order of 300–400 eV, the basic model does not apply. This may well explain why our hard X-ray emitting symbiotic stars with relatively large iron line equivalent width of the order of 117–580 eV could not be modeled using the power law plus reflection component model at the 0.1–10 keV energy band. However, hSSs could be modeled with power law plus reflection component at higher energy band 15–50 keV (see Chemyakova et al. (2005)). In our further search for a reflection component in our sources, we successfully modeled three out of our four sources with an absorbed bremsstrahlung plus reflection component (see Table 2 for fully modeled three out of our four sources with an absorbed bremsstrahlung plus reflection component). In our further search for a reflection component in our sources, we successfully modeled three out of our four sources with an absorbed bremsstrahlung plus reflection component (see Table 2 for fully modeled three out of our four sources with an absorbed bremsstrahlung plus reflection component). This strongly suggests the presence of reflection of Compton scattered hard X-rays from the accretion disks leading to the formation of the fluorescence iron line.

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 $N_H$ of the ambient matter. Of course, when $N_H$ 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 few AGN that showed absorption column densities of $N_H$ = $10^{23}$ 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 the hSSs 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 3, 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 $N_H$. Piro (1993) found that the EW generated by passage through optically-thin absorbing material is $\sim$ 100 eV x $A_{Fe}$ x $N_H^{23}$ x $f_1$, where $A_{Fe}$ is the Fe abundance to solar, $N_H^{23}$ is the column density in units of $10^{23}$ cm$^{-2}$ and $f_1$ is the total covering fraction of the absorber. In the case of CH Cyg, this would create an EW of either 220 eV (using only the full fraction) or 1120 eV using the weighted value.

In contrast to the CH Cyg situation, however, the other three sources show a much lower correlation between column density and the Fe Kα EW. T CrB has the lowest EW of the three sources but a significantly larger column density, measured either with with full-covering $N_H$ or via the weighted method, than either RT Cru or SS73 17. Of course, these two methods are merely approximate; a full calculation of the expected EW would require complete modeling of the geometry of the source and absorption system, including the arrangement of the “partial” covering. At the least, however, this discrepancy suggests that absorption is only one part of the observed EW in these systems.

4.4 The 6.7 and 7.0 keV Emission Lines

The He-like and H-like iron emission lines can be produced both by photoionization (and excitation) and collisional ionization/excitation in hot plasmas. It is a matter of which one dominates in any given source, which may not be simple to deduce. In the case of SS73 17, Eze et al. (2010) used high-resolution Chandra HETG to show that the G ratio in the Fe XXV lines, albeit heavily blended, was much more consistent with that of a collisional plasma than a photo ionized one. In addition, they showed that the H-like to He-like line ratio was consistent with the best-fit bremsstrahlung temperature of the system. Unfortunately, the accuracy of our He-like and H-like EW measurements is not adequate to constrain their ratios sufficiently to merit comparison with the measured bremsstrahlung temperature. In addition, the Suzaku CCDs do not have sufficient resolution to measure the G ratio from the Fe XXV line itself. However, we believe it is likely that the emission lines from the other three sources are dominated by thermal emission as well, although this could and should be tested with future Chandra HETG or Astro-H observations.

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**Fe Kα Line in Hard X-ray Emitting Symbiotic Stars**

**Table 1.** The symbiotic stars used in the work

| Source Name | ObsID   | Obs. start (UT) Date / Time (ks) |
|-------------|---------|---------------------------------|
| CH Cyg      | 40016020 | 2006-05-28 / 07:28 35.2         |
| T CrB       | 401043010 | 2006-09-06 / 22:44 46.3         |
| RT Cru      | 402040010 | 2007-07-02 / 12:38 50.9         |
| SS73 17     | 403043010 | 2008-11-05 / 16:30 24.9         |

**Table 2.** The reduced χ² for the absorbed bremsstrahlung, power law plus XSPEC reflect model and an absorbed bremsstrahlung plus XSPEC reflect model, F–test probability and reflection normalization

| Source Name | BM  | PRM | BRM | FP   | RN   |
|-------------|-----|-----|-----|------|------|
| CH Cyg      | 1.40| 5.56| 1.40| 0.29 | 0.00 |
| T CrB       | 1.19| 2.53| 1.18| 0.05 | 0.06 |
| RT Cru      | 1.14| 1.79| 1.12| 0.002| 0.17 |
| SS73 17     | 1.20| 2.57| 1.02| 3.61×10⁻⁸| 0.46 |

Parameters are the absorbed bremsstrahlung model (BM), power law plus XSPEC reflect model (PRM), an absorbed bremsstrahlung plus XSPEC reflect model (BRM), F–test probability of null result for the BRM (FP) and reflection normalization for the BRM (RN)

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Table 3. The Fe lines fit parameters.

| Source Name | $N_f^H$ | $N_p^H$ | $C$ | $kT$ | $E_{6.4}$ | $E_{6.7}$ | $E_{7.0}$ | EW_{6.4} | EW_{6.7} | EW_{7.0} |
|-------------|---------|---------|-----|------|-----------|-----------|-----------|----------|----------|----------|
| CH Cyg      | 22.0 ± 7.0 | 99^{+26}_{-37} | 0.91 ± 0.04 | 6^{+3}_{-2} | 6.41 ± 0.02 | 580^{+424}_{-65} | 6.59 ± 0.05 | 111^{+95}_{-35} | 6.81^{+0.12}_{-0.07} | 66^{+87}_{-38} |
| T CrB       | 17.7 ± 2.2 | 37 ± 6 | 0.71 ± 0.06 | 19^{+3}_{-2} | 6.43 ± 0.01 | 117^{+48}_{-35} | 6.72 ± 0.02 | 85^{+40}_{-22} | 7.01 ± 0.02 | 104^{+39}_{-41} |
| RT Cru      | 3.3 ± 0.4 | 58 ± 9 | 0.46 ± 0.05 | 29^{+5}_{-6} | 6.38 ± 0.01 | 174^{+38}_{-29} | 6.64 ± 0.01 | 52^{+34}_{-22} | 6.96 ± 0.01 | 51^{+37}_{-25} |
| SS73 17     | 9.2 ± 0.5 | 34 ± 5 | 0.65 ± 0.05 | 38 ± 6 | 6.38 ± 0.01 | 185^{+120}_{-63} | 6.67 ± 0.01 | 158^{+136}_{-41} | 6.95 ± 0.01 | 93^{+116}_{-40} |

Parameters are the hydrogen column density of the full-covering and the partial-covering matter in units of 10^{22} cm^{-2} ($N_f^H$ and $N_p^H$), the covering fraction of the partial-covering matter ($C$), the continuum temperature in keV ($kT$), 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 equivalent widths in eV (EW_{6.4}, EW_{6.7}, and EW_{7.0}).

Figure 1. Spectra of the symbiotic stars. In the upper panel, the data and the best-fit model are shown by crosses and solid lines, respectively. Each spectral component is represented by dotted lines. In the lower panel, the ratio of the data to the best-fit model is shown by crosses. The inset in the upper panel is an enlarged view for the Fe Kα complex lines.