HIGH-RESOLUTION X-RAY SPECTRA OF THE SYMBIOTIC STAR SS73 17

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ABSTRACT

SS73 17 was an innocuous Mira-type symbiotic star until the International Gamma-Ray Astrophysics Laboratory and Swift discovered its bright hard X-ray emission, adding it to the small class of “hard X-ray emitting symbiotics.” Suzaku observations in 2006 then showed it emits three bright iron lines as well, with little to no emission in the 0.3–2.0 keV bandpass. We present here follow-up observations with the Chandra High Energy Transmission Grating and Suzaku that confirm the earlier detection of strong emission lines of Fe Kα fluorescence, Fe XXV and Fe XXVI but also show significantly more soft X-ray emission. The high-resolution spectrum also shows emission lines of other highly ionized ions as Si XV and possibly S XVI. In addition, a re-analysis of the 2006 Suzaku data using the latest calibration shows that the hard (15–50 keV) X-ray emission is brighter than previously thought and remains constant in both the 2006 and 2008 data. The G ratio calculated from the Fe XXV lines shows that these lines are thermal, not photoionized, in origin. With the exception of the hard X-ray emission, the spectra from both epochs can be fit using thermal radiation assuming a differential emission measure based on a cooling-flow model combined with a full and partial absorber. We show that acceptable fits can be obtained for all the data in the 1–10 keV band varying only the partial absorber. Based on the temperature and accretion rate, the thermal emission appears to be arising from the boundary layer between the accreting white dwarf and the accretion disk.

Key words: accretion, accretion disks – binaries: symbiotic – line: formation

Online-only material: color figures

1. INTRODUCTION

Symbiotic stars are interacting binaries whose components are a red giant and hot companion which accretes mass from the stellar wind of the red giant, producing a blue continuum that ionizes the surrounding gas. In most symbiotic stars, the accretor is a white dwarf (WD), although some symbiotic stars (e.g., GX 1+4) have a neutron star companion (Chakrabarty & Roche 1997). In X-ray wavelengths, symbiotic stars were detected as moderately bright sources in the ROSAT/All Sky Survey. Mürset et al. (1997) examined 16 symbiotic stars seen with ROSAT and categorized them into three classes: (1) super soft emission from the photosphere of the WD (α-type), (2) emission from an optically thin thermal (kT ∼ 0.2 keV) plasma possibly due to colliding winds from the two stars or to accretion (β-type), and (3) an ill-defined category of relatively hard X-ray sources (γ-type). The origin of this hard emission remains uncertain to this day, and although not in the Mürset et al. (1997) survey, the ROSAT observation of SS73 17 suggests it would likely have been placed in category (3), albeit with some uncertainty due to the large column density (N_H = 1.8 × 10^{22} cm^{-2}) required to fit ROSAT data (Smith et al. 2008).

Earlier in 2005, both International Gamma-Ray Astrophysics Laboratory (INTEGRAL; IGRJ 10109-5746; Revnivtsev et al. 2006) and Swift (Swift J101103.3-574814; Tueller et al. 2005) independently discovered a hard X-ray source that Masetti et al. (2006) quickly identified with CD-57 3057 (SS73 17). Combined with a small group of objects—CH Cyg (Ezuka et al. 1998), RT Cru (Masetti et al. 2005; Luna & Sokoloski 2007), and T CrB (Tueller et al. 2005; Luna et al. 2008)—these sources form the “hard X-ray emitting symbiotics.” Afterward, a dedicated Suzaku observation of SS73 17 revealed the presence of strong iron lines in the 6–7 keV region (Smith et al. 2008), which pointed to a thermal origin for the X-ray emission. Another remarkable feature in the X-ray spectrum of SS73 17 is its highly absorbed soft X-ray emission (with N_H > 10^{23} cm^{-2}; Smith et al. 2008).

The origin of the hard and weak soft X-ray emission have remained a mystery which we hoped to address with a combination of Chandra High Energy Transmission Grating (HETG) and Suzaku observations. In Section 2, we summarize our observations and data processing; Section 3 contains our spectral analysis, while Section 4 presents the timing analysis. A discussion of our results is found in Section 5.

2. OBSERVATION AND DATA ANALYSIS

We observed SS73 17 with the Chandra High Energy Transmission Grating Spectrometer (HETGS) and the Suzaku X-ray Imaging Spectrometer (XIS) and Hard X-ray Detector (HXD). The HETG data have a spectral resolution of 0.012 Å and 0.023 Å FWHM for the High and Medium Energy Gratings (HEG, MEG), respectively. The Suzaku XIS data cover the 0.3–12 keV range with ∼150 eV resolution, while the HXD extends the energy coverage from 10 to 600 keV, although the source could not be detected above 50 keV. Details on the Suzaku instrumentation and calibration can be found in the Suzaku Web site.3 Our goal was to obtain simultaneous Suzaku and Chandra observations in both soft and hard X-rays. Due to the differing pointing constraints of the two telescopes, the observations were close together but not overlapping in time (see Table 1).

The Chandra and Suzaku observations dates and exposure times are shown in Table 1. Multiple (six in total) Chandra observations were done for operational reasons, but this fortunately allowed us to study the long-term variability of the source. CIAO 4.1 and CALDB 4.1 were used for the Chandra data analysis.

3 http://heasarc.gsfc.nasa.gov/docs/suzaku/astroegof.html
Each of the six observations was independently analyzed to obtain the Response Matrix Functions (RMFs) using the "mkrmf" script and the Ancillary Response Matrices (ARFs) files using the "fullgarf" script. After confirming that the spectral shape remains constant in all six observations to within our ability to measure it, we merged data from the six observations to increase the signal-to-noise ratio and obtain more reliable spectral fits. We used "add_grating_orders" and "add_grating_spectra" scripts to merge the grating orders and grating spectra, respectively. We expect to lose some sensitivity to line broadening due to this merging, which is acceptable since our results do not hinge upon the line width. The merged data has a total exposure time of 100.023 ks with 3557 and 3729 counts in the HEG and MEG arms, respectively, between 0.3 and 10 keV.

Both "Suzaku" observations were analyzed using version 2 of the standard "Suzaku" pipeline software; in the case of ObsID 401055010, this is an update from the version used in Smith et al. (2008). In both cases, the pointing direction was chosen to center SS73 17 on the HXD detector which has the effect of reducing the effective area of the XIS by 10% due to vignetting. We extracted all events within 4 of the source for the XIS detectors to produce our source spectra. Response matrices were generated for the XIS detectors using version 2009-02-28 of the xisrmfgen and effective area files for HXD-nominal pointing using xisarfgen. The XIS background spectra were extracted from a circular region with no apparent sources that were offset from both the source and the corner calibration sources.

We used only the HXD/PIN detector because the source was not bright enough to be detected in the HXD/GSO. We used the PIN response matrix appropriate for our data as generated by the "Suzaku" team. We obtained the PIN background events from HXD/PIN Background files for V2.x Processed Data and then used "mgtime" to merge the good time intervals to get common counts/bin.

- **Figure 1**: Top panel: HETG spectrum of SS73 17 in the 1.5–2.5 Å region, showing the fit to the iron lines using a bremsstrahlung continuum and six Gaussian lines. Note that the Fe xxv triplet in the middle is heavily blended, unlike the Fe Kα fluorescence line. Bottom panel: cash statistic residuals for the fit.

(A color version of this figure is available in the online journal.)

## Table 1

| Satellite | ObsID       | Start Date (mm/dd/yyyy) | Start Time (UT) | Exposure Time (ks) |
|-----------|-------------|-------------------------|-----------------|-------------------|
| Suzaku    | 401055010   | 06/05/2006              | 05:13:12        | 17.9              |
| Chandra   | 8967        | 10/23/2008              | 9:08:24         | 34.6              |
| Chandra   | 10765       | 11/5/2008               | 9:43:58         | 19.3              |
| Suzaku    | 403043010   | 11/11/2008              | 16:30:00        | 19.5              |
| Chandra   | 10859       | 1/20/2009               | 6:48:27         | 10.3              |
| Chandra   | 10793       | 1/21/2009               | 16:34:23        | 16.7              |
| Chandra   | 10860       | 2/24/2009               | 18:24:54        | 13.0              |
| Chandra   | 10869       | 2/28/2009               | 3:41:25         | 6.4               |

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4. [http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/pinbgd.html](http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/pinbgd.html)

5. [http://space.mit.edu/CXC/ISIS/](http://space.mit.edu/CXC/ISIS/)

3. SPECTRAL ANALYSIS AND RESULTS

### 3.1. Chandra HETG Spectral Analysis and Results

Spectral analysis of the Chandra HETG data was performed using the Interactive Spectral Interpretation System (ISIS). In Figures 1 and 2, we show the grating X-ray spectra of SS73 17 from the Chandra HETG observation. As shown in Figure 1, we modeled the spectrum using a thermal bremsstrahlung continuum with six Gaussian lines in the narrow λ = 1.5–2.5 Å bandpass. The best-fit values for the observed iron line positions, strengths, and Gaussian widths (σ) are given in Table 2; all errors in this and other tables are 90% confidence limits.

The relative positions of the Fe xxv triplet lines were fixed, although their overall position was allowed to vary. This is necessary because the individual lines are not resolved in the HEG. As a result of this partial blending, the individual line flux errors have large uncertainties although the overall detection of the Fe xxv lines is strong. We also fixed the relative positions of the Fe xxvi doublet; the mean position is given in Table 2.
We detected a few additional emission lines from Si\textsuperscript{xiv} and possibly S\textsuperscript{xvi} in the soft X-ray spectrum (Table 3). These lines could not have been detected in the original \textit{Suzaku} results due to the larger absorption seen during that observation. However, the single-temperature ($\sim$9.3 keV) thermal plasma model used in Smith et al. (2008) would not generate these lines for any value of the absorption column density. Si\textsuperscript{xiv}, for example, has its peak emission at 1.36 keV; and at 9.3 keV, these lines are only 5\% of their peak value (Smith et al. 2001). We therefore fit the overall spectrum (1.5–10 Å) using an absorbed (full and partial cover absorption) two-temperature (using the APEC (Smith et al. 2001) thermal plasma code) model. Our best-fit model shows that the system is heavily absorbed ($N_H$ full = 14.65 \times 10^{22} cm\textsuperscript{-2} for the full covering absorber and $N_H$ = 1.59 \times 10^{22} cm\textsuperscript{-2} for the full covering absorber) and the two plasmas have well-differentiated temperatures (with $kT_1 = 9.90$ keV and $kT_2 = 1.12$ keV; see Table 4 and Figure 1).

3.2. \textit{Suzaku} Spectral Analysis and Results

The \textit{Suzaku} data covers a much broader energy range than the HETG, albeit at a lower resolution. As it turns out, fitting this broad range with a single physically motivated model was quite difficult. As we will show here, we were unable to find a convincing fit over the entire bandpass, although we considered a number of possibilities. We were motivated, in part, by comparisons of the \textit{Suzaku} spectra from the first and second epoch which showed that the spectra in the 6–50 keV bandpass, including the iron lines, were unchanged while the lower energy spectra changed dramatically; see Figure 3. This suggested that the underlying X-ray source was relatively constant, while the absorber changed. We note that the soft X-ray flux in the second \textit{Suzaku} observation ($F_X(0.5–2$ keV) = 1.7 \times 10^{-13}$ erg cm\textsuperscript{-2} s\textsuperscript{-1}) is in much better agreement with the original \textit{ROSAT} observation ($\sim$4 \times 10^{-13} erg cm\textsuperscript{-2} s\textsuperscript{-1} based on a pointed count rate of 0.0253 counts s\textsuperscript{-1}) than the first \textit{Suzaku} observation (Bickert et al. 1996; Smith et al. 2008).
Tueller et al. (2005), there is a transient high mass X-ray binary, GRO J1008-57, 31' from SS73 17. Fortunately, the Swift BAT survey is now available via Skyview,6 and we were able to use this along with the BAT light curves of selected transient sources7 to determine the impact of GRO J1008-57. As shown in Figure 4, this source is outside the FWHM field of view of the PIN, although it is still within the range where emission can leak into the source at the 10%–15% level (see Figure 8.3 of the Suzaku proposer’s guide8). The apparent brightness of the GRO J1008-57 relative to SS73 17 is due to the former’s transient nature; during both Suzaku observations the source was in quiescence. An analysis of the light curves of both sources using the BAT transient Web site shows that the average 15–50 keV flux of SS73 17 is $\sim 1.7 \pm 0.2 \times 10^{-11} \text{ erg cm}^{-2} \text{s}^{-1}$, while the average quiescent GRO J1008-57 flux is $(1.9 \pm 0.2) \times 10^{-11} \text{ erg cm}^{-2} \text{s}^{-1}$. A simple power-law fit to the HXD PIN data alone from both Suzaku observations returns a 15–50 keV flux (not including particle or cosmic X-ray backgrounds) of $(2.9 \pm 0.4) \times 10^{-11} \text{ erg cm}^{-2} \text{s}^{-1}$. This difference from the Swift/BAT result could be due to a fluctuation in the source itself, or due to calibration differences between the BAT and the PIN; we note there is an 18% offset between the Suzaku XIS and PIN detectors due to calibration uncertainties.9

As contamination seemed unlikely to resolve the question of the missing flux, we considered two alternative sources of hard X-ray emission: (1) a reflection component from the accretion disk, or (2) an additional highly absorbed power-law component from a possible unseen jet in the system. Adding a reflection component resulted in a good fit from 1–50 keV, but unfortunately required an unphysical solid angle for reflection of $R \equiv \Omega/2\pi > 3$, even for a face-on disk. Reeves et al. (2009), who faced similar circumstances when modeling the quasar PDS 456, found a plausible fit to the spectrum of the Seyfert 2 with $R = 1.3$. However, while a value slightly in excess of 1 for the parameter $R$ can be understood if the underlying source is in fact more absorbed than the fit suggests, but a value $R > 3$ would require a significant increase in the underlying accretion rate. Patterson & Raymond (1985), in the context of accreting cataclysmic variable systems, found that accretion rates much above $2 \times 10^{-10} M_\odot \text{ yr}^{-1}$ would quench the hard X-ray emission because the region around the boundary layer of the accretion disk would become optically thick. We also found that the addition of a power-law component with $\Gamma = 1.04 \pm 0.13$ and intrinsic $F_X(15–50 \text{ keV}) = 2.1 \times 10^{-11} \text{ erg cm}^{-2} \text{s}^{-1}$, absorbed by the same

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6 http://skyview.gsfc.nasa.gov
7 http://swift.gsfc.nasa.gov/docs/swift/results/transients/
8 http://heasarc.gsfc.nasa.gov/docs/astro/prop_tools/suzaku_td/node11.html
9 See Suzaku Memo 2008–2006 available at ftp://legacy.gsfc.nasa.gov/suzaku/doc/xrt/suzakumemo-2008-06.pdf
two components as the cooling-flow plasma, also significantly improves the fit in the 15–50 keV bandpass, although with only the weak physical justification that there could be a (unseen) jet in system generating a relatively flat synchrotron spectrum.

4. TIMING ANALYSIS

The cornerstone of our timing analysis is the comparison between the ratio of measured fractional rms variation, $s$, to that expected from Poisson fluctuations alone, $s_{\text{exp}}$ (see Luna & Sokoloski 2007). In Figure 5, we show the light curves from Suzaku and Chandra, respectively. All the light curves were extracted in three energy bands—0.3–5.0, 5.0–10.0, and 12.0–50.0 keV—dividing the spectral regions where absorption is important and binned at 360 s and 64 s. The values of the $s/s_{\text{exp}}$ ratio are listed in Table 6.

The value of $s/s_{\text{exp}}$ indicates that SS73 17 has strong stochastic variability in all the energy ranges observed. During both Suzaku observations the fractional amplitude of the stochastic variations was higher in the 5.0–10.0 keV band than in the 0.3–5.0 and 12.0–50.0 keV ranges, both in the 64 s (except for ObsID 403043010) and 360 s binned light curves. Chandra observations show that SS73 17 is sometimes more variable in the high energies than in the soft band.

We also searched for modulated emission in the light curves. Using the arrival times of the source events, we calculated the $Z_{\text{1}}^2$ (Rayleigh) statistic (Buccheri et al. 1983) for frequencies
f_{\text{min}} = 1/T_{\text{exp}} \text{ to } f_{\text{max}} = 1/2t_{\text{frame}} \text{ with } \Delta f = 1/T_{\text{exp}}, \text{ where } T_{\text{exp}} \text{ is the exposure time as listed in Table 1, } t_{\text{frame}} \text{ is the readout time (2.54204 s in the case of } Chandra \text{ and 8 s in the case of } Suzaku \text{ XIS). We do not detect periods in the light curves. Using Equation (1) from Luna & Sokoloski (2007), during } Chandra \text{ observations we were sensitive to oscillations with a fractional amplitudes from 13\% to 26\%. In this case, we analyze the six observation segments separated. The higher number of counts obtained with } Suzaku \text{ allows us to search for pulsations with a fractional amplitude as low as 4\%, although again we did not find modulation in the light curves.}

5. DISCUSSION AND CONCLUSIONS

Symbiotic stars have been poorly studied because in the optical, only limited information can be obtained: most of the interesting activity in these systems is, in fact, occurring in other bands. In addition, only a relative handful have been identified, \approx 200 (Belczynski et al. 2000) out of an estimated 1200–15,000 symbiotic stars with WD accretors only in our Galaxy (Lü et al. 2006). SS73 17 appears to be one of an even smaller category of “hard X-ray emitting symbiotics,” as noted above. The most significant question is why such a small number of systems (e.g., SS73 17, CH Cyg, T CrB, and RT Cru) emits in hard X-rays (Kennea et al. 2009) while most symbiotics are faint, soft X-ray emitters (Müser et al. 1997). Kennea et al. (2009) hypothesized that, unlike typical symbiotics, these systems contain particularly high-mass WDs, making them potential type Ia progenitors.

The most likely source of the hard X-ray emission from these symbiotic stars is the same as in CVs—the boundary layer between the accretion disk and the WD (e.g., Luna & Sokoloski 2007). In the case of SS73 17, Smith et al. (2008) noted that it is a strong hard X-ray source heavily absorbed in the soft X-rays, which we confirm with these follow-up } Chandra \text{ and } Suzaku \text{ observations. We detected the same strong Fe X-ray emission lines, but with some additional soft X-ray emission lines, and an increased soft X-ray continuum as well. Our partial success with fits using a constant source and a variable partial absorber agrees with the picture suggested by Kennea et al. (2009), where the changing spectrum is due primarily to the absorbing material moving in and out of our line of sight. Curiously, despite the long-term spectral changes that primarily affect the low (< 5 keV) energy spectrum and can therefore be described by changes in the partial absorber, our timing analysis shows that the short-term stochastic variations are larger when absorption is higher (compare } s/s_{\text{exp}} \text{ for the first and second } Suzaku \text{ observations). This, somehow, could be linked to changes in the accretion rate, i.e., more mass flowing through the disk, increasing the amount of absorption and increasing the viscosity in the disk. Our analysis also points that, in general, the hard component (5–10 keV) is more variable than its soft counterpart. In a cooling-flow scenario, we would expect a more turbulent plasma as it gets colder. This discrepancy, however, could be due to poor photon statistics in the soft X-ray band, although an increase in the bin size of the light curves, aiming at improving the signal-to-noise in each bin, would hinder the search for short-term variability.

The inadequacies of the fit at low energies could be due to a number of causes. We can suggest at least three possible sources for the soft X-ray emission. It could be due to photoionization of the red giant wind by the WD, as proposed by Wheatley & Kallman (2006), or could be created in a colliding wind shock between the M-type giant and the compact object. Alternatively, these soft X-rays could be due to a wider range of emission measures from the thermal plasma which are only partially absorbed by a thick layer of gas and dust. With the available data, it is not possible to distinguish between these models.

The data do show that the hard X-rays from SS73 17 are largely thermal, due to the presence of a number of emission lines with clear thermal origin. We found that both the forbidden (z) and resonance (w) Fe xxv lines are present in the spectrum. The HETG results show that the Fe xxv lines are heavily blended with a G ratio \((\approx (x + y + z)/w = 1.29^{+1.0}_{-1.0})\) that supports a wide range of temperatures. However, this value is much lower than would be expected from a photoionized plasma \((\approx 4\text{;}\text{ Porquet & Dubau 2000})\). In addition, the Fe xxvi/Fe xxv ratio is in good agreement with the temperature inferred from a bremsstrahlung model fit to the continuum. This thermal picture is further confirmed by the Si xiv emission line and the likely detection of X xvi, which have been observed in a similar symbiotic system (CH Cyg).

The results from the } Suzaku \text{ observations suggest that the source is moderately variable in the long term primarily due to changes in the absorption. This is not surprising for an X-ray binary. However, the constancy of the Fe Kα fluorescent line suggests that the mechanism generating this line is largely independent of the absorption, challenging the model presented in Smith et al. (2008). They suggested that about half \((0.13 \text{ keV})\) of the Fe Kα fluorescence was due to line-of-sight scattering in the absorbing medium, with 0.1 keV also coming from scattering off the surface of the WD. The new fits would predict only 0.065 keV from the absorbing material, or 0.165 keV in total, significantly less than the required amount.

**Table 6**  
Value of the } s/s_{\text{exp}} \text{ for Each Observation Listed in Table 1}

| Satellite/ObsID | 64 s          | 360 s          | 64 s          | 360 s          |
|----------------|---------------|---------------|---------------|---------------|
| Suzaku...      | 0.3–5.0 keV   | 5.0–10 keV    | 12.0–50.0 keV | 0.3–5.0 keV   |
| 401055010...   | 3.58          | 4.44          | 1.18          | 3.80          |
| 403043010...   | 2.17          | 1.90          | 1.22          | 3.30          |
| Chandra...     |               |               |               |               |
| 8967...        | 1.26          | 1.23          | ...           | 1.83          |
| 10765...       | 1.25          | 1.50          | ...           | 1.21          |
| 10859...       | 1.10          | 1.12          | ...           | 1.57          |
| 10793...       | 1.25          | 1.12          | ...           | 1.29          |
| 10860...       | 1.17          | 1.15          | ...           | 1.02          |
| 10869...       | 1.40          | 1.78          | ...           | 2.35          |
Many questions remain about these unusual symbiotic systems. We have been able to confirm the thermal origin of most of the hard X-rays, although some fraction of the flux in the 15–50 keV band—the bandpass where this system was first noted by INTEGRAL and the Swift BAT—remains unexplained. However, it is worth to note that INTEGRAL observations of RT Cru were well fit with a non-thermal power-law emission with photon index $\Gamma = 2.7$ (Chernyakova et al. 2005); therefore we cannot discard the possibility that some fraction of the flux in 15–50 keV band from SS73 17 has a non-thermal origin. However, it is still not at all clear if these systems are wind or disk accretors, and ultimately what drives the hard X-ray flux. More observations to determine the mass of the primary and/or secondary, as well as the orbital period of the system, would be extremely helpful in future modeling efforts.

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