HEXTE STUDIES OF SCO X–1 SPECTRA: 
DETECTIONS OF HARD X–RAY TAILS 
BEYOND 200 keV

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ABSTRACT

Using the HEXTE experiment on-board the RXTE satellite, we performed a search for hard X–ray tails in Sco X–1 spectra. We found strong evidence for the presence of such a non–thermal component on several occasions. Using the PCA/RXTE we were able to track the position of the source along the Z diagram, and we observed that the presence of the hard X–ray tail is not confined to a particular region. However, we found a correlation between the power law index of the non–thermal component and the position of the source in the Z diagram, suggesting that the hard X–ray spectrum (i.e., $E > 50$ keV) becomes flatter as the mass accretion rate increases. We were also able to study the temporal variation of the appearance/absence of the hard X–ray component. With our derived luminosities, we were also able to test the idea that X–ray luminosities can be used to distinguish between X–ray binary systems containing neutron stars and black holes.

INTRODUCTION

It is well established, after the GRANAT/SIGMA and CGRO missions, that a power–law spectra extending beyond 30 keV are not exclusive signatures of a black hole in an X–ray binary system (Barret and Vedrenne, 1994; Barret, McClintock, and Grindlay, 1996). High sensitivity observations with RXTE (e.g., Heindl and Smith, 1998; Barret et al., 2000) have shown the presence of hard X–ray flux in other types of low–mass X–ray binaries (LMXBs) and BeppoSAX observations also have detected hard X–ray flux from LMXBs systems (see, e.g., Frontera et al., 2000; Iaria et al., 2000; Di Salvo et al., 2000).

In this work we studied the hard X–ray spectrum of Sco X–1, a high luminosity LMXB Z source, using the High Energy X–ray Timing Experiment (HEXTE) on–board RXTE. The presence of a non–thermal component in Sco X–1 spectra has been historically reported (e.g., Peterson and Jacobson, 1966; Haymes et al., 1972; Duldig et al., 1983), but much more sensitive searches have failed to detect such a component, placing strong upper limits on the non–thermal flux (e.g., Greenhill et al. 1979; Rothschild et al., 1980; Soong and Rothschild, 1983). Recently, Strickman and Barret (2000) reported the presence of a hard X–ray tail in Sco X–1 using CGRO/OSSE. Thanks to the HEXTE sensitivity, we show here, on several occasions, strong evidence for the presence of this variable non–thermal component extending up to 220 keV.

This present study is an extension of a previous work (D’Amico et al., 2000) with the use of an expanded database from the public RXTE archive of Sco X–1 observations, containing data from 1997 April to 1999 July. Our on–source time (for the Proportional Counter Array, PCA) is 203,440 s in 22 subsets of data (an improvement factor of 30 % over our previous study) which, in turn, provided us with more than 100 ks of on–source live time in HEXTE. In the next sections we describe our data selection and analysis, then we discuss the detection of a non–thermal component and present our conclusions.
Fig. 1. Spectrum resulting from a bremsstrahlung + power law fit to data subset 20053-01-02-00 (a), and the result of a bremsstrahlung fit to subset 30035-01-04-00 (b), showing the presence/absence of a hard X–ray tail in Sco X–1. Residuals are given in units of standard deviations (lower panels). In (b) the upper limits are $2\sigma$ including the 60–80 keV bin which experienced a $-3\sigma$ residual. The $\chi^2_\nu$ are 1.27 and 1.62 respectively.

**DATA SELECTION AND ANALYSIS**

We used data from HEXTE (Rothschild et al., 1998) to search for hard X–ray tails in Sco X–1 in the $\sim 20$–220 keV interval and data from PCA (Jahoda et al., 1996) to determine the position of the source in the Z diagram. We have chosen, from the public RXTE database of Sco X–1, those subsets of data in which $\gtrsim 5000$ s of HEXTE total on–source time was available, in order to achieve good sensitivity at high energies, resulting in 22 RXTE observations (as of 2000 August) that cover the period from 1997 April to 1999 July. If, in a particular observation, the source was moving back and forth from the normal to the flaring branch (see, e.g., van der Klis, 1995), then we split the data according to the branch resulting in the 28 observation segments displayed in Table 1. Since we are primarily interested in the study of the non–thermal ($\gtrsim 50$ keV) spectra of the source (the “hard” component of the spectrum), we have simply modeled the (HEXTE) low energy thermal component as thermal bremsstrahlung emission.

We refer the reader to D’Amico et al. (2000), for a more detailed description of the instrument and data analysis.

**RESULTS**

We developed two criteria to determine the presence of a hard X–ray tail in a particular spectrum: 1) a signal to noise ratio (SNR) $\geq 5$ in the 75–220 keV energy range, and 2) an F–Test null significance for the addition of the hard component at a level of $10^{-7}$ or less. We claim that we observed a hard X–ray tail only when both of these criteria are fulfilled. We have 8 clear detections of non–thermal flux in Sco X–1 spectra, with the hard X–ray tail extending at least to 220 keV. The spectral parameters derived for those observations are shown in Table 2. Similarly, we defined a strong non–detection when 1) the SNR in the 75–220 keV is $< 1$, and 2) the F–Test was at a level of $\gtrsim 10^{-5}$. We thus observed (see Table 1) 4 strong non–detections. We note that several of our observations have very significant F–Test values, but with an SNR $< 5$. In those cases we do not claim that we have observed a hard X–ray tail, although this is an open possibility. In Figure 1 we show one of our clear detection spectra, together with a spectrum when we have not detected a hard component.

We observed a variation of a factor of $\sim 3$ in the flux of the non–thermal component in the 20–200 keV
| OBSID     | MJD   | No. | Z Pos | Live Time\(^a\) | SNR\(^b\) | F\(^c\)     | Flux\(^d\)     | Hard Tail (Y/N) |
|----------|-------|-----|-------|------------------|-----------|-------------|----------------|-----------------|
| 20053-01-01-00 | 50556 | 1   | HB    | 6341             | 10.6      | 4.4E−15     | 8.57+1.02-1.92 | Y               |
| 20053-01-01-02 | 50558 | 2   | NB    | 5434             | 4.2       | 1.7E−7      | 4.05+0.57-0.97 | N               |
| 20053-01-01-03 | 50559 | 3   | NB    | 5896             | 4.8       | 3.9E−9      | 5.20+0.75-0.74 | N               |
| 20053-01-01-05 | 50561 | 4   | NB    | 1908             | 0.8       | 6.2E−5      | 6.29+1.77-1.77 | N               |
| 20053-01-01-08 | 50561 | 5   | FB    | 4593             | 2.4       | 7.7E−4      | 2.47+1.94-1.94 | N               |
| 20053-01-01-05 | 50562 | 6   | NB    | 8558             | 7.3       | 3.5E−13     | 8.63+0.91-0.90 | N               |
| 10061-01-03-00 | 50815 | 7   | NB    | 5484             | 4.2       | 2.7E−9      | 5.48+0.69-0.74 | N               |
| 20053-01-02-00 | 50816 | 8   | FB    | 8145             | 18.6      | 5.8E−12     | 13.6+2.0-2.0   | Y               |
| 20053-01-02-03 | 50819 | 9   | NB    | 5686             | 3.5       | 2.7E−9      | 5.91+0.96-0.96 | N               |
| 30036-01-01-000 | 50820 | 10  | FB    | 6858             | 5.8       | 3.8E−7      | 7.73+1.62-1.65 | N               |
| 20053-01-02-02 | 50820 | 11  | FB    | 4193             | 4.9       | 3.3E−4      | 3.44+1.23-1.23 | N               |
| 30036-01-02-000 | 50821 | 12  | NB    | 4370             | 2.2       | 3.6E−4      | 4.50+0.90-0.90 | N               |
| 30036-01-02-000 | 50821 | 13  | FB    | 2527             | 1.8       | 3.6E−4      | 2.83+1.05-1.06 | N               |
| 30400-02-0200 | 50872 | 14  | NB    | 2326             | 2.5       | 1.0E−6      | 4.03+1.13-1.13 | Y               |
| 30400-02-0200 | 50872 | 15  | FB    | 3125             | < 0       | 0.08        | < 2.20         | N               |
| 30035-01-01-000 | 50963 | 16  | HB    | 6253             | 6.2       | 1.2E−14     | 3.63+0.92-0.92 | N               |
| 30035-01-03-000 | 50965 | 17  | NB    | 3750             | 1.3       | 2.4E−8      | 3.20+0.86-0.89 | N               |
| 30035-01-03-000 | 50965 | 18  | FB    | 2318             | < 0       | 0.03        | < 2.67         | N               |
| 30035-01-04-000 | 50966 | 19  | FB    | 6230             | < 0       | 0.38        | < 1.00         | N               |
| 40020-01-01-000 | 51186 | 20  | NB    | 2669             | 6.6       | 1.2E−7      | 6.10+2.1.10-2.10 | Y               |
| 40020-01-01-000 | 51186 | 21  | NB    | 4233             | 3.5       | 3.3E−8      | 3.77+1.66-1.65 | N               |
| 40020-01-01-000 | 51187 | 22  | FB    | 8000             | 8.1       | 2.2E−9      | 7.40+2.46-2.46 | N               |
| 40020-01-01-000 | 51188 | 23  | NB    | 2836             | 1.8       | 1.1E−3      | 3.00+1.26-1.26 | N               |
| 40020-01-01-000 | 51188 | 24  | FB    | 1822             | 1.8       | 0.11        | 2.95+2.12-2.12 | N               |
| 40020-01-01-000 | 51189 | 25  | SA    | 4316             | 2.9       | 5.6E−4      | 2.57+0.88-0.87 | N               |
| 40020-01-03-000 | 51193 | 26  | HB    | 3578             | 6.2       | 9.8E−10     | 8.45+1.94-1.94 | Y               |
| 40706-01-01000 | 51433 | 27  | NB    | 8076             | 2.8       | 1.4E−5      | 2.09+0.53-0.53 | N               |
| 40706-01-01000 | 51433 | 28  | FB    | 2167             | 2.2       | 1.2E−3      | 2.45+1.04-1.07 | N               |

Note: HB=Horizontal Branch, NB=Normal Branch, FB=Flaring Branch; SA=Soft Apex; No.=observation number

\(^a\) total live time for HEXTE, in s

\(^b\) signal to noise ratio in the 75-220 keV energy range

\(^c\) probability that a better fit occurred due to a random chance

\(^d\) flux in the 75–220 keV energy range, in units of \(10^{-10}\) ergs cm\(^{-2}\) s\(^{-1}\); apart from the 5 detections of a hard X-ray tail, the photon index used for the non–thermal component was our average value of \(~1\); uncertainties are given at 90% confidence level
Luminosity in the same energy range is below $10^{37}$ ergs s$^{-1}$, the weaker atoll sources hard X–ray luminosities reported by Barret, McClintock, and Grindlay (1996).

Table 1, for observation 20 we detected a hard X–ray tail, which was not present 4 hours later in observation 21. To our knowledge, this is the first time that such a short time–scale variability in the hard component is reported in our entire database.

We were also able to study the time–scale of variations of the hard X–ray component. As can be seen in Figure 2b, one other interesting and suggestive relationship (Figure 2c) is that the hard component flattens as the mass accretion rate ($\dot{M}$) increases, if we assume that the movement along the Z diagram (from the horizontal to the flaring branch) is the result of the increasing variation of the $\dot{M}$ (see, e.g., van der Klis, 1995). Thus it is possible to speculate that the mechanism responsible for the production of the hard X–ray tail in observations 20 and 22, BATSE/OSSE did not. Meanwhile, in observation 26 the hard X–ray tail was detected both by HEXTE and BATSE/OSSE, with a spectrum extending up to $\sim 400$ keV.

Our measured luminosities in the 2–20 keV ($L_x$) and 20–200 keV energy intervals ($L_{hx}$) can be used to account for our entire database.

We have observed the presence of a hard X–ray tail in each of the 3 branches on the Z diagram. Although it is unclear what is producing the hard X–ray tail in Sco X–1, as can be seen in Figure 3a, it appears that the chance of observing a hard X–ray tail is greater if the thermal component is brighter. This assumes that the thermal component observed in HEXTE 20–50 keV band can be used to trace its $E < 20$ keV behavior. When we do observe a hard component, the power law index is correlated with the soft component temperature. (Figure 3b). One other interesting and suggestive relationship (Figure 3c) is that the hard component flattens as the mass accretion rate ($\dot{M}$) increases, if we assume that the movement along the Z diagram (from the horizontal to the flaring branch) is the result of the increasing variation of the $\dot{M}$ (see, e.g., van der Klis, 1995). Thus it is possible to speculate that the mechanism responsible for the production of the hard X–ray tail is the declining variation of the $\dot{M}$ in Sco X–1 (Bradshaw, Fomalont, and Geldzahler, 1999), we found (using the PCA data) Sco X–1 to be emitting near the Eddington level in the 2–20 keV band (for a 1.4 $M_\odot$ neutron star). This is remarkably different from the atoll sources (Barret et al., 2000), in which the luminosity in the same energy range is below $10^{37}$ ergs s$^{-1}$ when a hard tail is detected. The 20–200 keV hard component luminosity variation between our 8 detections is 5.9–15.0 $\times 10^{35}$ ergs s$^{-1}$, which is comparable to the weaker atoll sources hard X–ray luminosities reported by Barret, McClintock, and Grindlay (1996).

We also note that on all 3 occasions that the source was in the HB, a hard X–ray tail was detected.

### DISCUSSION

Taking 2.5 kpc as the lower limit to the distance to Sco X–1 (Bradshaw, Fomalont, and Geldzahler, 1999), we found (using the PCA data) Sco X–1 to be emitting near the Eddington level in the 2–20 keV band (for a 1.4 $M_\odot$ neutron star). This is remarkably different from the atoll sources (Barret et al., 2000), in which the luminosity in the same energy range is below $10^{37}$ ergs s$^{-1}$ when a hard tail is detected. The 20–200 keV hard component luminosity variation between our 8 detections is 5.9–15.0 $\times 10^{35}$ ergs s$^{-1}$, which is comparable to the weaker atoll sources hard X–ray luminosities reported by Barret, McClintock, and Grindlay (1996).

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We also note that on all 3 occasions that the source was in the HB, a hard X–ray tail was detected.

### Table 2: Hard X–ray Tail Detections in Sco X–1

| OBSID          | No. | kT (keV) | Flux$^a$ | Power–Law | Flux$^b$ | $\chi^2$ | Z Pos. |
|----------------|-----|----------|----------|-----------|----------|----------|--------|
| 20053-01-01-00 | 1   | 4.83$^{+0.03}_{-0.05}$ | 9.03$^{+0.39}_{-0.36}$ | 1.75$^{+0.22}_{-0.20}$ | 1.56$^{+0.10}_{-0.11}$ | 1.59     | HB     |
| 20053-01-01-06 | 6   | 4.50$^{+0.05}_{-0.05}$ | 5.83$^{+0.27}_{-0.30}$ | 1.64$^{+0.27}_{-0.29}$ | 0.91$^{+0.10}_{-0.11}$ | 1.06     | NB     |
| 20053-01-02-00 | 8   | 4.36$^{+0.03}_{-0.03}$ | 7.16$^{+0.26}_{-0.24}$ | -0.17$^{+0.30}_{-0.33}$ | 1.23$^{+0.13}_{-0.14}$ | 1.26     | FB     |
| 30036-01-01-000| 10  | 4.28$^{+0.03}_{-0.04}$ | 9.63$^{+0.42}_{-0.41}$ | -0.71$^{+0.63}_{-0.70}$ | 0.62$^{+0.11}_{-0.11}$ | 1.29     | FB     |
| 30035-01-01-00 | 16  | 4.51$^{+0.08}_{-0.07}$ | 7.45$^{+0.00}_{-0.06}$ | 2.37$^{+0.28}_{-0.28}$ | 1.04$^{+0.08}_{-0.06}$ | 1.09     | HB     |
| 40020-01-01-00 | 20  | 4.54$^{+0.06}_{-0.07}$ | 4.07$^{+0.24}_{-0.30}$ | 1.00$^{+0.53}_{-0.15}$ | 0.75$^{+0.16}_{-0.15}$ | 1.13     | NB     |
| 40020-01-01-02 | 22  | 4.41$^{+0.02}_{-0.02}$ | 7.46$^{+0.15}_{-0.15}$ | -0.49$^{+0.42}_{-0.24}$ | 0.66$^{+0.12}_{-0.12}$ | 1.67     | FB     |
| 40020-01-03-00 | 26  | 4.69$^{+0.05}_{-0.05}$ | 6.20$^{+0.25}_{-0.25}$ | 1.36$^{+0.27}_{-0.24}$ | 1.24$^{+0.13}_{-0.15}$ | 1.80     | HB     |

Note: bremsstrahlung + power law model used; uncertainties are given at 90% confidence level for the derived parameters of the model applied.

$^a$ Flux in 20–50 keV range in units of $10^{-9}$ ergs cm$^{-2}$ s$^{-1}$

$^b$ Flux in 20–200 keV interval in units of $10^{-9}$ ergs cm$^{-2}$ s$^{-1}$
Fig. 2. a) The thermal flux as measured by HEXTE (in units of $10^{-9}\text{ergs cm}^{-2}\text{s}^{-1}$) for our entire database, which suggests that the chance of observing a hard X-ray tail (triangles) is higher when the thermal component is brighter. Squares are strong non-detections of a hard component (see Table 1) and asterisks are treated as intermediate cases (see text). b) When a hard tail is observed, there is also some tendency for it to be steeper as the temperature of the thermal component increases. c) Plotting the power-law observed against the branch in the Z suggests that a higher $\dot{M}$ makes the hard X-ray spectrum flatter (see text for details). In (c), HB, NB and FB were arbitrarily spaced along the x axis.

to study the suggestion (Barret et al., 2000) that such luminosities can be used to distinguish between neutron star and black hole systems, with neutron stars systems emitting $L_{hx} \sim L_x$ when $L_x \lesssim L_{crit}$, with $L_{crit} = 1.5 \times 10^{37}\text{ergs s}^{-1}$. Since Sco X–1 is emitting close to the Eddington level, our observations can not be used to test the hypothesis for the 2–20 keV luminosity (see details in Barret et al., 2000). Otherwise our observations of $L_{hx}$ are in agreement with the idea that only black hole binaries can have both $L_x$ and $L_{hx}$ above $L_{crit}$.

CONCLUSIONS

In this paper, we provided clear evidence for variable hard X-ray emission from the Z source Sco X–1. We observed that the 20–200 keV non-thermal component varied by at least an order of magnitude. We were able to track the movement of the source along the Z diagram and we concluded that the presence of the hard X-ray tail is not confined to a particular position in such a diagram, which may suggest that the mechanism responsible for the production of the hard X-ray tail is not uniquely dependent on the inferred $\dot{M}$. Otherwise we speculated that the appearance of a hard component in the spectrum may be related to the brightness of the thermal component, and that the shape of the X-ray tail may be correlated with the temperature of the thermal component.

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