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A HARD X-RAY VIEW OF SCORPIUS X-1 WITH *INTEGRAL*: NONTHERMAL EMISSION?

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ABSTRACT

We present here simultaneous *INTEGRAL*/*RXTE* observations of Sco X-1 and in particular a study of the hard X-ray emission of the source and its correlation with the position in the Z track of the X-ray color-color diagram. We find that the hard X-ray (above about 30 keV) emission of Sco X-1 is dominated by a power-law component with a photon index of ∼3. The flux in the power-law component slightly decreases when the source moves in the color-color diagram in the sense of increasing inferred mass accretion rate from the horizontal branch to the normal branch/flaring branch vertex. It becomes not significantly detectable in the flaring branch, where its flux has decreased by about an order of magnitude. These results present close analogies to the behavior of GX 17+2, one of the so-called Sco-like Z sources. Finally, the hard power law in the spectrum of Sco X-1 does not show any evidence of a high-energy cutoff up to 100–200 keV, strongly suggesting a nonthermal origin of this component.

Subject headings: accretion, accretion disks — stars: individual (Scorpius X-1) — stars: neutron — X-rays: binaries — X-rays: general — X-rays: stars

1. INTRODUCTION

Hard X-ray emission in the brightest low-mass X-ray binaries (LMXBs), the so-called Z sources, was occasionally detected in the past (see, e.g., Peterson & Jacobson 1966). These results received relatively little attention, mostly because the lack of a broadband spectral coverage did not permit one to establish whether an extra component was indeed required to fit the hard spectrum of these sources. Renewed interest in the hard X-ray emission properties of bright LMXBs was motivated by recent broadband studies mainly performed with the *Rossi X-Ray Timing Explorer* (*RXTE*; 2–200 keV) and *BeppoSAX* (0.1–200 keV). These have shown that most Z sources display variable, hard power-law–shaped components, dominating their spectra above ∼30 keV (see Di Salvo & Stella 2000 for a review).

The hard component detected in bright (otherwise soft) LMXBs can be fitted by a power law, with photon index in the range 1.9–3.3, contributing from 1% to 10% of the observed (0.1–200 keV) source luminosity. The presence of these components in Z sources seems sometimes to be related to the source state or its position in the X-ray color-color diagram (CD). The clearest example to date is in the *BeppoSAX* observation of GX 17+2, where the hard component (a power law with photon index of ∼2.7) showed the strongest intensity in the horizontal branch (HB) of its CD (Di Salvo et al. 2000). A factor of 20 decrease was observed when the source moved from the HB to the normal branch (NB), i.e., from low to high (inferred) mass accretion rate. A hard tail was also detected in almost all the currently known Z sources (e.g., Di Salvo et al. 2001, 2002; Iaria et al. 2001; Asai et al. 1994). The fact that a similar hard component has been observed in several Z sources indicates that this is probably a common feature of these sources. However, the origin of this hard component is still poorly understood. While in most cases the hard component becomes weaker at higher accretion rates, High-Energy X-Ray Timing Experiment (HEXTE) observations of Sco X-1 showed a hard power-law tail in five out of 16 observations, without any clear correlation with the position in the CD (D'Amico et al. 2001). The thermal versus nonthermal nature of this component remains to be addressed, yielding important information on the production mechanism.

Sco X-1, the brightest persistent X-ray source in the sky, is also the brightest radio source among neutron star LMXBs, with a mean radio flux about 10 times higher than that of the other Z sources (e.g., Fender & Hendry 2000). A hard X-ray power-law component has been observed in *RXTE* HEXTE (20–200 keV) data of this source (D'Amico et al. 2001). As already mentioned, contrary to the case of GX 17+2, in Sco X-1 the flux of this component was observed to vary without any clear correlation with the position in the CD. Interestingly, Strickman & Barret (2000) report that the hard X-ray emission present in OSSE data of Sco X-1 may be correlated with periods of radio flaring.

To study the hard X-ray emission in Sco X-1, the brightest of these sources, as well as its correlation with other source properties (such as radio emission and fast timing variability), we have performed a campaign of observations of Sco X-1 with the *International Gamma-Ray Astrophysics Laboratory* (*INTEGRAL*) and *RXTE*. Part of these observations were also done simultaneously with radio VLBI observations (which will be discussed elsewhere). The *INTEGRAL* spectrum of Sco X-1 shows with high statistical significance the presence of a hard (power-law) component, without any clear exponential cutoff up to ∼100–200 keV. We also find clear evidence that the intensity of this component is correlated with the position of the source in the X-ray CD.

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2. OBSERVATIONS AND ANALYSIS

Sco X-1 was observed during two complete *INTEGRAL* revolutions on 2003 July 30–August 1 and 2003 August 11–13. The *INTEGRAL* payload consists of two main γ-ray instruments, a spectrometer, SPI (Vedrenne et al. 2003), and an imager, IBIS, and of two monitor instruments, the X-ray monitor JEM-X (3–35 keV; Lund et al. 2003) and the Optical Monitoring Camera (*V* band, 500–600 nm; Mas-Hesse et al. 2003). The IBIS instrument (Ubertini et al. 2003) covers the energy range between 20 keV and 8 MeV with two detectors, ISGRI (Lebrun et al. 2003) and PICsIT (Di Cocco et al. 2003) and has a field of view of 29° × 29° at half-sensitivity (9° × 9° fully coded) with a point-spread function of 12′ FWHM. The SPI also covers the energy range between 20 keV and 8 MeV with a field of view (FOV) of 31° diameter (16° fully coded) and an angular resolution of $2^\circ\!.5$.

Observations were performed in the usual *INTEGRAL* format; i.e., the observation was split in separate exposures (“science windows”), each lasting ~3600 s, followed by a 5 minute slew. The exposures were arranged following a 5 × 5 dither pattern. The IBIS and SPI instruments were operated in standard mode during the whole observation, while JEM-X was in a nonstandard mode (SPEC), which, unfortunately, is not yet calibrated. We therefore discarded the JEM-X data from our analysis. The effective exposure time was 372 ks for IBIS and 358 ks for SPI.[12] The IBIS data were analyzed using the standard analysis procedures of OSA version 5 and the latest response matrices (2004 October) rebinned to 26 channels between 15 and 800 keV and the latest spectral extraction routines (Goldwurm et al. 2003). A systematic error of 1% was applied to all the *INTEGRAL* ISGRI spectra.

During all the observations, Sco X-1 was the only source detected in the wide FOV of the instruments. The source coordinates as derived from the ISGRI mosaic image in the 20–35 keV energy band are R.A. = $16^{\rm h}19^{\rm m}54^{\rm s}\!.9$, decl. = $-15^\circ38'34''\!.4$ (uncertainty $\pm10''$, 1 σ confidence level) at about $10''$ from the SIMBAD position (McNamara et al. 2003).

To study the source spectral state in the standard X-ray band, we also analyzed data from the Proportional Counter Array (PCA; Zhang et al. 1993) on board *RXTE*, which consists of five co-aligned Proportional Counter Units (PCUs), with a total collecting area of 6250 cm^2 and an FOV, limited by collimators, of 1° FWHM, sensitive in the energy range 2–60 keV. The *RXTE* observation, performed simultaneously with the *INTEGRAL* observation, is divided into two parts of 175 ks each, approximately 2 weeks apart from each other. We selected intervals for which the elevation angle of the source above the Earth limb was greater than 10°. On a few occasions, some of the five PCUs were off; we therefore used only data from PCUs 2 and 3, which where on for most of the observation. The X-ray CD of Sco X-1 during the *INTEGRAL* observations, obtained from the PCA data, is shown in Figure 1. During each of the two observations, the source described a fairly complete Z track in the CD.

In order to check for the presence of the hard tail in our data, we first analyzed the *INTEGRAL* (IBIS/ISGRI, energy band 20–200 keV) spectrum integrated over the whole observation (see Fig. 2, *left panel*). Similar to what has been done for other LMXBs of the Z class, we fitted the *INTEGRAL* spectrum with the Comptonization model `compTT` (whose description is given in Titarchuk 1994). `Comptt` is an analytical model describing the thermal Comptonization of soft photons (for which a Wien spectrum is assumed) inverse Compton scattered in a hot electron cloud with optical depth τ and whose temperature can range from a few to 500 keV. This model includes relativistic effects and works for optically thick and optically thin regimes. The geometry of the Comptonizing cloud can be either spherical or disklike. In this Letter, we assume a spherical geometry (this assumption only affects the value of the optical depth derived from the fit).

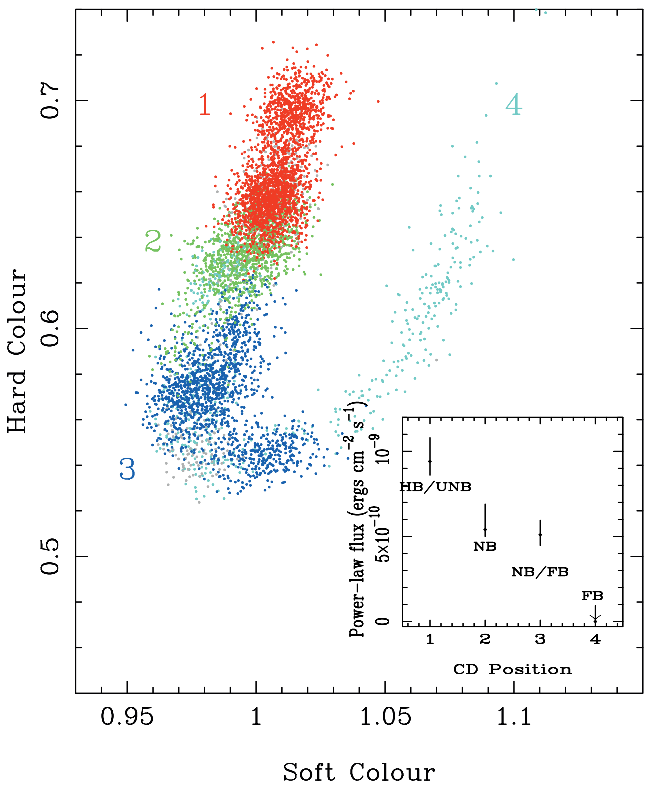

FIG. 1.—Color-color diagram of Sco X-1 from PCA data during the simultaneous *INTEGRAL*/*RXTE* observation. Here “Soft Color” is the ratio of the count rate in the energy bands [3.5–6 keV]/[2–3.5 keV] and “Hard Color” is the ratio [9.7–16 keV]/[6–9.7 keV], respectively. To take into account possible small gain changes during the *RXTE* observations, the hard and soft colors of Sco X-1 are normalized with respect to the colors (calculated in the same energy range) obtained from *RXTE* observations of Crab acquired close to the dates of our observations. Only data form PCUs 2 and 3, which were on for most of the observation, have been used. The four colors indicate the four regions (also indicated with numbers from 1 to 4) in which the CD has been divided, from which *INTEGRAL* spectra were extracted. *Inset*: Measured power-law flux in the 20–200 keV range plotted for each of the four CD-resolved spectra.

This model gives a good fit of the soft part of the Sco X-1 spectrum up to ~40–50 keV. Above this energy, a hard excess is clearly visible in the residuals, independently of the particular Comptonization model used to fit the soft part of the spectrum. The fit is significantly improved by adding to the `compTT` model a power law with photon index ~3.1 (this gives a reduction of the χ^2/degrees of freedom [dof] from 892/13 to 14.4/11). We tested the presence of a thermal cutoff in the hard power law; substituting the power law with a cutoff power law (that is, a power law multiplied by an exponential cutoff) does not improve the fit significantly (the latter model gives a $\chi^2/{\rm dof} = 15.6/10$), and the temperature of the exponential cutoff is $kT > 200$ keV (90% confidence level). The best-fit parameters for the ISGRI (20–200 keV) spectrum are reported in Table 1; data and residuals with respect to the best-fit model are shown in Figure 2 (*left panel*).

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[12] Due to the much lower statistics of the SPI data, we concentrate here on the analysis of ISGRI data of Sco X-1.

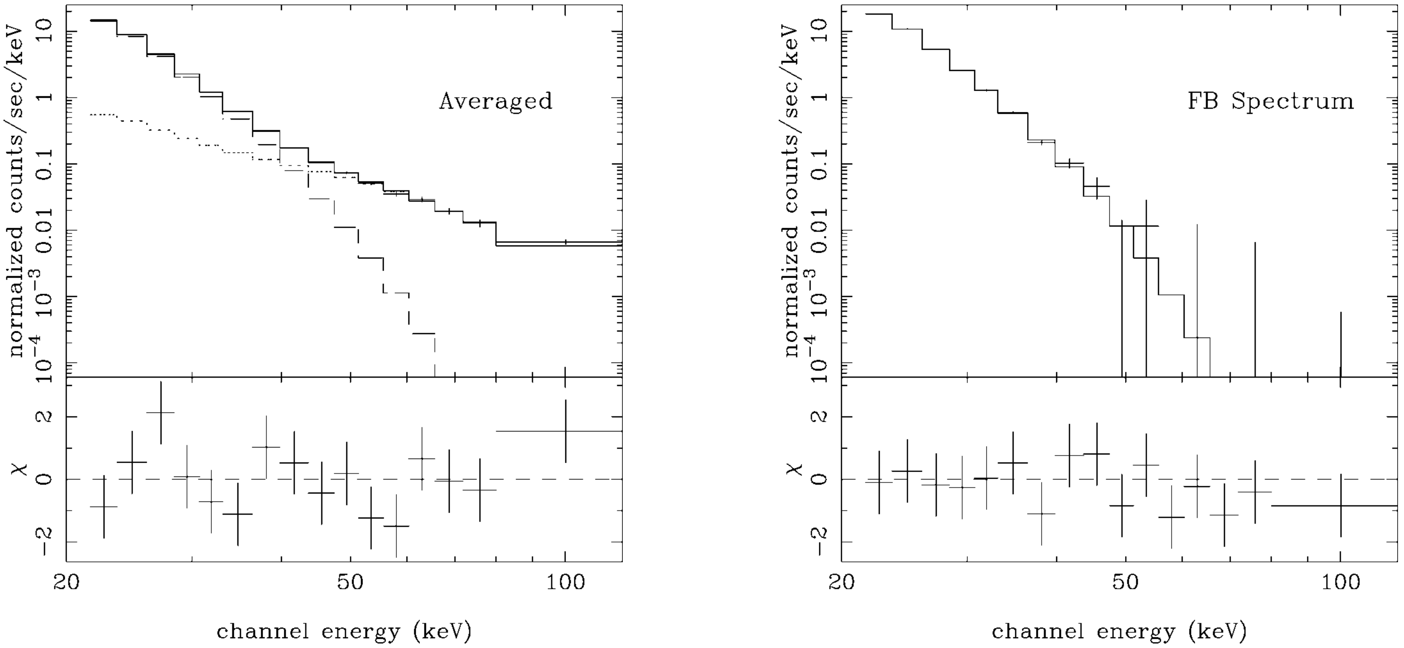

FIG. 2.—*Left*: ISGRI (20–200 keV) averaged spectrum (*left*) and FB spectrum (*right*) of Sco X-1 together with the best-fit model (*solid line on top of the data*) composed of the Comptonization model (`comptt`; *dashed line*) and a cutoff power law (*dotted line*). *Right*: Residuals in units of σ with respect to the best-fit models shown in Table 1.

To look for variability in the hard component with the spectral state of the source, as measured by its position in the X-ray CD, we divided the Z track in the CD of Sco X-1 into four parts corresponding to the HB/upper NB, the NB, the flaring branch (FB), and the NB/FB vertex, respectively. We therefore extracted *INTEGRAL* ISGRI spectra for each of the time intervals mentioned above, resulting in four CD-resolved spectra. Unfortunately, there was no superposition between *RXTE* and *INTEGRAL* data in the FB during the first part of the observation. The *INTEGRAL* ISGRI exposure times for the four intervals were 52.4, 45.5, 60.6, and 6 ks. We fitted each of these spectra with `comptt` and a cutoff power law. This model gave a good fit of the first three spectra, with little variability in the spectral parameters (see Table 1). For three of these spectra, the hard power-law component was required in order to fit the data. Remarkably, the FB spectrum did not require a power-law component and could be fitted with a simple Comptonization model (see Fig. 2, *right panel*). Including the power law in the spectral fit of the FB spectrum, with the photon index fixed at 3.1, a good fit requires a decrease of the normalization of the power-law component by a factor of at least 5 with respect to the average spectrum. In Table 1, we show the total X-ray flux of Sco X-1 calculated in the 20–40 keV and in the 40–200 keV energy range, "Flux (20–40)" and "Flux (40–200)," respectively. While the Flux (20–40) decreases from the HB to the NB/FB vertex and then increases when the source goes to the FB, the Flux (40–200) always decreases, varying by about 1 order of magnitude when the source moves from the HB to the FB.

Although from Table 1 there seems to be a clear trend of the 40–200 keV flux to decrease from the HB to the NB and FB

TABLE 1

RESULTS OF THE FITTING OF THE SCO X-1 *INTEGRAL* ISGRI (20–200 keV) SPECTRA

Parameter	Averaged	HB/Upper NB	NB	NB/FB	FB
			`comptt` + Cutoff Power-Law Model		
kT_0 (keV)	1.6 (frozen)	1.6 (frozen)	1.6 (frozen)	1.6 (frozen)	1.6 (frozen)
kT_e (keV)	$3.31^{+0.02}_{-0.04}$	$2.95^{+0.11}_{-0.02}$	3.43 ± 0.02	$3.42^{+0.03}_{-0.27}$	3.14 ± 0.20
τ	$5.70^{+0.10}_{-0.05}$	$8.5^{+1.0}_{-0.9}$	5.35 ± 0.11	5.21 ± 0.12	$6.5^{+1.7}_{-1.1}$
PhoIndex	3.12 ± 0.07	$3.11^{+0.17}_{-0.50}$	$2.70^{+0.43}_{-0.93}$	$3.20^{+0.21}_{-0.66}$	3.1 (frozen)
kT (keV)	>220	>70	>160	>118	…
Flux (20–40)	6.1 ± 0.2	7.12 ± 0.41	5.85 ± 0.37	4.43 ± 0.50	7.31 ± 0.45
Flux (40–200)	2.6 ± 1.8	3.7 ± 1.6	2.5 ± 1.8	1.85 ± 0.89	0.36 ± 0.36
$\Delta\chi^2$	878	464	164	102	…
χ^2/dof	15.6/10	7.0/10	10.8/10	12.9/10	7.5/12
			`comptt` + `pegpwrlw` Model		
PhoIndex	$3.31^{+0.08}_{-0.17}$	$3.29^{+0.33}_{-0.22}$	$3.04^{+0.32}_{-0.62}$	$3.59^{+0.65}_{-0.42}$	3.1 (frozen)
Flux (20–200)	6.27 ± 0.35	$9.4^{+1.4}_{-0.8}$	$5.4^{+1.5}_{-0.4}$	$5.10^{+0.85}_{-0.63}$	<0.93
χ^2/dof	14.4/11	6.8/11	11.3/11	13.0/11	7.5/12

NOTES.—The model consists of a Comptonized spectrum modeled by `comptt` and a cutoff power law or the `pegpwrlw` model to fit the hard component; kT_0 is the temperature of the seed photon (Wien) spectrum, kT_e is the electron temperature, and τ is the optical depth in a spherical geometry. Fluxes (20–40) and (40–200) are the total flux from the source in units of 10^{-9} ergs cm^{-2} s^{-1} in the 20–40 keV energy range and in units of 10^{-10} ergs cm^{-2} s^{-1} in the 40–200 keV energy range, respectively. On the other hand, Flux (20–200) is the power-law flux in the 20–200 keV range in units of 10^{-10} ergs cm^{-2} s^{-1}. The value $\Delta\chi^2$ is the variation of χ^2 for the addition of a power law to the model. Note that the addition of a power law does not change the χ^2 for the FB spectrum; χ^2/dof is the final reduced χ^2 for the best-fit model. All the uncertainties are calculated at the 90% confidence level, and upper limits at the 95% confidence level.

vertex, the uncertainties on the hard X-ray flux are still quite large to draw a firm conclusion. In fact, in order to calculate the flux in a given energy range and the associated uncertainty, XSPEC needs to use the total best-fit model, which includes both the `comptt` and the cutoff power-law component; each of these components has several parameters, and the uncertainties on all the parameters are taken into account in the calculation of the source flux and its uncertainty. If we are interested in knowing the flux of the hard power-law component alone in a given energy range (to see how this component evolves when the source moves in the X-ray CD), it is more convenient to use the model named `pegpwrlw` in XSPEC. This model allows one to directly calculate the power-law flux in a given energy range (20–200 keV is our choice) and the associated uncertainty. We therefore substituted the cutoff power-law model with the `pegpwrlw` model to fit the *INTEGRAL* spectra of Sco X-1. The results of the fits with the `comptt` plus `pegpwrlw` model are also reported in Table 1 (since the parameters of the `comptt` did not change significantly, these are shown only once in the table). The decrease of the power law 20–200 keV flux along the CD is evident. For clarity, we have also plotted these power-law fluxes in Figure 1 (*inset*).

3. DISCUSSION

We report on a spectral analysis of a simultaneous ∼300 ks long observation of Sco X-1 with *INTEGRAL* and *RXTE*. We show that the addition of a hard power-law component dominating the X-ray spectrum above ∼30 keV proves necessary for a good fit of the *INTEGRAL* (20–200 keV) spectrum. The power law is quite steep, with a photon index of about 3.1, contributing up to 12% of the observed 20–200 keV luminosity, and does not show any evidence of a high-energy cutoff up to 100–200 keV. Similarly to what was observed in the *BeppoSAX* observation of the Z source GX 17+2, the presence of the hard component in Sco X-1 seems to be related to the position of the source in the Z track; in fact, we observe a clear trend of the 20–200 keV power-law flux to decrease when the inferred mass accretion rate increases (i.e., from the HB to the NB/FB vertex). At the highest inferred mass accretion rate (i.e., in the FB of the X-ray CD), the hard X-ray emission seems to disappear completely (the hard X-ray flux decreases by about 1 order of magnitude with respect to the flux measured in the HB/upper NB). Note, however, that the behavior of the hard component in the FB may be variable (see D'Amico et al. 2001).

One of the most interesting results of this analysis is that the hard power law detected in Sco X-1 does not show any evidence of a high-energy cutoff, with lower limits on the electron temperature that are in most cases above 100 keV (the lower limit on a thermal cutoff in the Sco X-1 averaged *INTEGRAL* spectrum, where the statistics is the highest, is about 200 keV). Such high temperatures are not expected in a system like Sco X-1, because of the strong Compton cooling due to the primary soft spectrum, where most of the energy is emitted. These results therefore indicate that, in analogy with the steep hard power-law emission detected in some soft states (e.g., intermediate and very high) of systems containing a black hole candidate, which do not show any energy cutoff up to a few hundred keV, the hard power law observed in Z sources may be of nonthermal origin.

The most probable origin of these components is therefore Comptonization in a hybrid thermal/nonthermal corona (where the Maxwellian velocity distribution of the electrons have a nonthermal high-velocity tail; e.g., Poutanen & Coppi [1998]; see Farinelli et al. [2005] and D'Aí et al. [2006] for a successful application of this model to the case of GX 17+2 and Sco X-1, respectively). For instance, it is possible that a hard population of electrons is accelerated in internal shocks at the base of a jet. Otherwise, the hard power law may originate in a mildly relativistic ($v/c \gtrsim 0.5$) bulk motion of matter close to the compact object. Therefore, nonthermal Comptonization in outflows (or jets) may be the origin of these components, with flatter power laws corresponding to higher optical depths of the scattering medium and/or higher bulk electron velocities (e.g., Psaltis 2001).

It has been proposed that nonthermal, high-energy electrons, responsible for the hard tails observed in Z sources, might be accelerated in a jet (Di Salvo et al. 2000). This is also confirmed by the observed correlation between the strength of the hard X-ray emission and the position of the source in the X-ray CD. In fact, all Z sources are detected as variable radio sources with the highest radio flux associated with the HB and the lowest with the FB (Migliari & Fender 2006 and references therein). In other words, both the radio emission from these objects, which is probably due to jets (Fender & Hendry 2000), and the hard X-ray emission are anticorrelated with the inferred mass accretion rate. In this respect, it will be very important to study the direct correlation between the presence and strength of the hard X-ray emission and the radio activity of the source. The radio (VLA) observations of Sco X-1, simultaneous to part of the *INTEGRAL* observations, is under investigation and will be discussed elsewhere.

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