Broadband spectral evolution of Scorpius X-1 along its Color-Color Diagram

Antonino D’A1, Piotr Zycki2, Tiziana Di Salvo1, Rosario Iaria1, Giuseppe Lavagetto1, N. Renato Robba1

1 Dipartimento di Scienze Fisiche ed Astronomiche, Università di Palermo, via Archirafi n.36, 90123 Palermo, Italy
2 CAMK, Bartycka 18, 00-716 Warsaw, Poland

We analyze a large collection of RXTE archive data of the bright X-ray source Scorpius X-1 in order to study the broadband spectral evolution of the source for different values of the inferred mass accretion rate by selecting energy spectra from its Color-Color Diagram. We model the spectra with the combination of two absorbed components: a soft thermal component, which can be interpreted as thermal emission from an accretion disk, and a hybrid Comptonization component, which self-consistently includes the Fe Kα fluorescence line and the Compton reflected continuum. The presence of hard emission in Scorpius X-1 has been previously reported, however, without a clear relation with the accretion rate. We show, for the first time, that there exists a common trend in the spectral evolution of the source, where the spectral parameters change in correlation with the position of the source in the CD. Using a hybrid thermal/non-thermal Comptonization model (EQPAIR code), we show that the ratio of the power supplied to the non-thermal distribution to the total power injected into the Comptonizing plasma correlates with the accretion rate, being the highest at the lowest accretion rates.

§1. Introduction

Scorpius X-1 is the brightest persistent X-ray source in the sky. The X-ray source is an old, low magnetized neutron star (NS), accreting matter transferred through Roche-lobe overflow from a low-mass companion. Scorpius X-1 is a prototype of the class of the Low-Mass X-ray Binaries (LMXBs), and assuming a distance of 2.8 ± 0.3 kpc (1), the source emits close to the theoretical Eddington limit for a 1.4 M⊙ NS (LEdd ∼ 2 × 1038 erg s⁻¹). The source belongs to the subclass of the Z-sources 2), showing in its Color-Color Diagram (CD) the classical three-shaped branches describing the Z pattern: the Horizontal Branch (HB) at the top of the Z track, followed by the Normal Branch (NB) and the Flaring Branch (FB) at the bottom of the pattern. There are strong indications (3) suggesting that what drives the changing in the spectral and temporal properties of LMXBs is the instantaneous accretion rate (M), which, for Z sources, is believed to increase monotonically from the HB to the FB.

In this article we report preliminary results of an investigation of the spectral properties of Scorpius X-1 through an extensive analysis of RXTE archive data, showing a connection between position of the source on the CD and spectral behavior.
§2. Data reduction and spectral analysis

We collected, using the RXTE data archive, pointed observations for \( \sim 288 \) ks long time exposure. We obtained energy-dependent lightcurves from PCU2 data, which we used to derive the CDs. We gathered pointed observations close in time (less than a week), obtaining four different Z-tracks, from which we selected a total of 22 different regions in order to cover a homogeneous part of the Z-track pattern and to have at the same time a suitable statistics. From these selections we derived the good time intervals (GTI) which we used for extracting the corresponding PCA and HEXTE spectra. Data have been further processed using the standard selection criteria, using PCU2 events for the PCA (3-32 keV range) and Cluster A events for the HEXTE (20-200 keV range). We have associated an energy dependent systematic error as in 4). No systematic error has been associated to the HEXTE data. A normalization constant is left free to vary between the PCU2 and HEXTE spectra to take into account residual flux calibration uncertainties.

We fitted our data with a model given by the sum of a soft DISKBB component (6) plus the recently developed thermal/non-thermal hybrid Comptonization model named EQPAIR (see 7, for a full description of the model). Following 5), we fixed the value of the equivalent hydrogen column to \( 3 \times 10^{21} \) cm\(^{-2} \), for each fit performed. Normalization and inner disk temperature were free to vary parameters of the DISKBB component, while we left free to vary the following parameters for the EQPAIR component: the soft seed-photon temperature of the Comptonizing cloud \( kT_0 \), the optical depth of the cloud \( \tau \), the hard to soft compactness ratio \( l_h/l_s \), the non-thermal to thermal power injected in the Comptonizing cloud \( l_{nth}/l_h \) and a normalization factor. This model contains a self-consistent computation of the reflection component, for which we set as free parameters \( \Omega/2\pi \), \( \xi \) and also the inner radius of the disk, \( R_{in} \) (in units of \( GM/c^2 \)), which is a measure of the relativistic smearing of the Fe K\( \alpha \) line in proximity of the NS. The value of the soft compactness \( l_s \) was unconstrained by the fit (it is mainly driven by the pair production rate, which manifests itself with the annihilation line at energies \( \sim 500 \) keV, far beyond our energy band), and we set it at a reference value of 10 (see also 8). All the other parameters of the model were frozen at the default values. We show in Fig. 3, right panel, the spectral decomposition of a typical spectrum taken from a selected region on the HB, with the contribution of each spectral component on the total emission.

§3. Discussion and Conclusions

We have examined 22 energy spectra of Scorpius X-1 in the 3.0–200 keV energy band using PCA and HEXTE spectra; the spectra have been extracted from selected regions chosen in the X-ray CD. We produced a CD for each close in time dataset in order to avoid shifts of instrumental origin, and repeated our analysis for each CD obtained in this way, thus having at hand a robust representation of the spectral evolution of the source in all its accretion states. To fit the spectra we adopted a model, which substantially differ from previously adopted modelizations of the Z-sources. We interpret the higher energy tail of Sco X-1 as a result of a hybrid
thermal/non-thermal Comptonization. Adopting this model, we find an adequate
description of the spectral behavior of the source for every spectrum in any region
of the CD. The values in reduced $\chi^2$ range from 0.37 to 2.01. For 15 spectra we
obtained a reduced $\chi^2$ value $\leq$ 1.0, for 6 spectra the value was below 1.5 and just in
one case above. Given the page limitation of this presentation we do not show the
best-fitting parameters for each spectrum, but we discuss the main physical spectral
characteristics as a whole. An extensive version of these results will be addressed in
a forthcoming paper. The soft thermal disk component of the spectrum is dominant
only at energies $\leq$ 5 keV, and contributes for less than 10% to the 3–200 keV energy
flux, independently of the selected energy spectrum. For this reason the exact shape
of the component is poorly constrained by the fits and will be omitted in the following
discussion. We focus our attention on the hard Comptonized component and its
thermal/non-thermal behavior.

![Non-thermal heating fraction versus total heating](image1)

**Fig. 1.** Non-thermal heating fraction versus total heating.

![Spectral decomposition of the total 3–200 keV emission](image2)

**Fig. 2.** Spectral decomposition of the total 3–200 keV emission in the $E^2 f(E)$ representa-
tion.

<table>
<thead>
<tr>
<th>Spectral Parameter</th>
<th>$l_h/l_s$</th>
<th>$kT_0$</th>
<th>$l_{nth}/l_h$</th>
<th>$\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HB</td>
<td>0.65</td>
<td>0.87</td>
<td>11.7</td>
<td>9.8</td>
</tr>
<tr>
<td>NB</td>
<td>0.48</td>
<td>0.91</td>
<td>8.4</td>
<td>8.5</td>
</tr>
<tr>
<td>bottom FB</td>
<td>0.39</td>
<td>1.08</td>
<td>4.5</td>
<td>8.0</td>
</tr>
<tr>
<td>top FB</td>
<td>0.61</td>
<td>1.08</td>
<td>4.7</td>
<td>11.0</td>
</tr>
</tbody>
</table>

**Table I.** Summary of fit results with a hybrid Comptonization model: average values for spectra
sharing the same position on the CD as obtained from the best-fitting models to data.

We summarize in Table 3 the range in which the best-fitting values of the continuum
parameters of the EQPAIR component lie for spectra in the same CD position.
The soft to hard compactness assumes a wide range of values, driving most of the
spectral evolution of the source; because the soft compactness is a frozen parameter,
the $l_h/l_s$ ratio gives immediately the power supplied to the plasma electron cloud,
which increases from the bottom of the FB to the HB. Spectra taken at the top of the
FB are hard ($l_h/l_s \simeq 0.61$) and optically thicker ($\tau \simeq 11$) than any other spectrum
observed. This might be related to a different accretion state of the source, which
becomes highly super-Eddington. We find that the soft seed-photon temperature
of the Comptonization well correlates with the position of the source in the CD,
being the highest on the FB and gradually decreasing as the source moves to lower
accretion rates. The ratio of the non-thermal to the thermal power supplied to the electron hybrid plasma clearly indicates that the non-thermal distribution rises up as the source moves from high to low accretion rates. Our spectral model suggests that the non-thermal contribution depends on the state of the source, being the strongest at lower accretion rates, namely on the HB. This behavior is in agreement with the behavior of the other Z sources. Moreover, this is the first strong detection that an hybrid thermal/non-thermal state smoothly changes according to the accretion state. For the 22 examined spectra, when the soft seed photon temperature is plotted versus the fraction of the non-thermal compactness parameter $l_{nth}/l_h$, there is a clear trend to have higher $l_{nth}/l_h$ values for lower photon temperatures, while this corresponds to higher values of the total heating luminosity $l_h$ (see Fig. 3). A recent INTEGRAL observation of this source (20-200 keV energy range) results in agreement with our results (9), thus confirming the association between position on the CD and hard X-ray behavior. Integral data seem also to hint to a non-thermal origin of this component, as no high-energy cut-off was present in the spectra that showed the hard-tail. Theoretical spectra and energetic contribution according to the relevant physical parameters involved in the case of a strict coupling with inflow (i.e. accretion to the compact object through the formation of an accretion disk) and outflow (i.e. jets), are a promising way to cover in a self-consistent way all the phases of accretion. An attempt to explicitly compute a jet spectrum, from radio to hard X-rays, has been recently proposed by 10), where the jet base subsumes the role of the static Comptonizing corona; spectral fits in the case of BH systems (namely Cyg X-1 and GX 339-4) in hard states are consistent with this scenario, but BH soft states and NS systems spectra need yet to be tested in order to understand the limits of validity of the jet model.

References