Spectral evolution of the X-ray nova XTE J1859+226 during its outburst observed by BeppoSAX and RXTE

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X-ray novae

A group of about 30 X-ray binaries that exhibit dramatic outbursts, generally at all wavelengths, caused by changes in the mass accretion rate

Light curves characterized by a FRED profile with typical time scales of weeks to months. Flaring activity sometimes superposed to the main LC

Classical theory of transient behaviour is based on the disk instability model. However an alternative mechanism was proposed by Wood et al. (2001) to explain the double outburst of XTE J1118+480

Most (if not all) of them enter the outburst in the hard state and also show radio emission (Brocksopp et al. 2002)
Black Hole Binaries in the Milky Way

- Sun
- Mercury
- Cyg X-1
- GRS 1915+105

**Companion Star**
- Accretion disk and black hole

**Catalogs**

- XTE J1118+480
- XTE J1859+226
- GRS 1009-45
- GRS 1124-683
- GS 2000+25
- H1705-250
- A0620-00
- GRO J0422+32
- SAX J1819.3-2525
- GRO J1655-40
- 4U 1543-47
- GX 339-4
- GS 2023+336
- XTE J1550-564
About XTE J1859+226

First detected by the ASM on October 9, 1999 at galactic coordinates l=54.05deg, b=8.61deg with an intensity of about 160 mCrab (Wood et al. 1999)

FRED-like light curve, rise time of 5 days, maximum intensity about 1.4 Crab and e-folding time of about 23 days

Outburst detected also by BATSE: the hard X-ray flux reached its maximum while the soft flux was still increasing

Three types of 1-10 Hz Quasi Periodic Oscillations detected with RXTE (Casella et al. 2007).

For C-type QPOs (Q > 10), evidence of a strong anti-correlation between the QPO frequency and the RMS variability

A strong radio counterpart detected on October 11, 1999 at a flux density of about 11 mJy at 15 GHz with Ryle telescope and VLA

Compact object mass of M=7.7+/1.3 M\textsubscript{sun} determined by Shaposhnikov & Titarchuk (2009) using the scaling method technique
The available data set

129 RXTE observations
From Oct. 11, 1999
To Jul. 24, 2000

6 BeppoSAX TOOs

Oct. 15, 1999
Oct. 22, 1999
Oct. 28, 1999
Nov. 7-8, 1999
Nov. 19-20, 1999
Mar. 26-27, 2000
The initial part of the source outburst was analyzed by Shaposhnikov & Titarchuk (2009) using RXTE data.
The spectral analysis

The broad-band BeppoSAX energy coverage (0.1-200 keV) allows to distinguish among models much better than RXTE

Methodological approach

Spectral analysis first with BeppoSAX

→

Same models applied to RXTE
Spectral component: the soft one

Usually both in Neutron Star and Black Hole X-ray binaries, both simple BB and multicolor-BB models have been used.

Could we phenomenologically distinguish among them?

Using the COMPTB model (Farinelli et al. 2008) it is possible to check whether deviation from a simple BB is present in the soft X-ray spectrum.

\[
S(E) \propto \frac{E^\gamma}{e^{E/kTs} - 1}
\]

\(\gamma = 3\) blackbody
\(\gamma \neq 3\) modified blackbody (MBB)

Asymptotic low-energy limit \(E \ll kTs\)

\[
S(E) \propto E^{\gamma - 1}
\]

\(\gamma < 3\) flatter spectrum (DBB-like)
\(\gamma > 3\) sharper spectrum (Wien-like)
Spectral component: the hard one

We used BMC to describe the high-energy part of the spectrum

\[ F(E) = \frac{C_n}{A+1} \left[ BB(E) + A \times BB(E) \ast G(E, E_0) \right] \]

Why using BMC instead of other often-used Comptonization models available in XSPEC (CompTT, CompPS)?

It is a *generic* Comptonization model, the Comptonization spectrum is simply given by the convolution of the seed BB spectrum with a broken-PL Green’s function.

The high-energy part of the spectrum can be fitted without any physical limitation in the applicability of the model.
Free parameters of BMC

1) The temperature of the blackbody seed photons $kT_{bb}$

2) The energy index $\alpha$ of the Green’s function, which observationally corresponds to the energy index of the powerlaw part of the high-energy spectrum

3) The illumination parameter $\log(A)$

4) The seed photon normalization
Five over six BeppoSAX TOOs shows that a simple BB does not well describes the soft X-ray emission (< 4 keV)

- BB+BMC  ➔  NO
- MODBB+BMC  ➔  YES, with \( \gamma < 2 \)

Thus MODBB+BMC and DISKBB+BMC are the best-fit models for BeppoSAX. Both models provide the same \( \chi^2 \)-value.

DISKBB+BMC applied to RXTE data even though in this case also BB+BMC works well (because of energy threshold > 3 keV)
Excellent agreement between BeppoSAX and RXTE, the spectral analysis works also as a calibration test among the two satellites
BeppoSAX/RXTE DISKBB parameters vs MJD
Example of spectral components with BeppoSAX

Cut-off powerlaw

Pure powerlaw
A complete view of the source spectral evolution

A very interesting peculiarity: during the very soft state the spectral index $\Gamma$ is closer to values typical of the hard state

<table>
<thead>
<tr>
<th>Obs.</th>
<th>$\Gamma$</th>
<th>$F_{\text{disk}}/F_{\text{tot}}$</th>
<th>RMS 0.1-64 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>RXTE First ID</td>
<td>1.5±0.04</td>
<td>0.43</td>
<td>30%</td>
</tr>
<tr>
<td>TOO1</td>
<td>2.15±0.04</td>
<td>0.56</td>
<td>20%</td>
</tr>
<tr>
<td>TOO2</td>
<td>2.15±0.04</td>
<td>0.56</td>
<td>16%</td>
</tr>
<tr>
<td>TOO3</td>
<td>2.17±0.08</td>
<td>0.64</td>
<td>12%</td>
</tr>
<tr>
<td>TOO4</td>
<td>1.8±0.08</td>
<td>0.77</td>
<td>5%</td>
</tr>
<tr>
<td>TOO5</td>
<td>1.81±0.10</td>
<td>0.75</td>
<td>&lt;5%</td>
</tr>
<tr>
<td>TOO6</td>
<td>1.86±0.05</td>
<td>0.67</td>
<td>No statistics</td>
</tr>
</tbody>
</table>
A very important point: careful use of the Comptonization models

Substitute BMC with e.g. COMPPS

Hard state

$kT_{bb} = 0.96 \pm 0.4$ keV
$kT_e = 25 \pm 3$ keV
$\tau = 2.9 \pm 0.6$
$F_{0.1-200\text{keV}} \approx 2 \times 10^{-8}$
ergs cm$^{-2}$ s$^{-1}$

If the transition from hard to soft is driven by an increase of $\dot{M}$ and $\tau \propto \dot{M}$ how is it possible that $\tau_{HS} > \tau_{SS}$?

Soft state

$kT_{bb} = 1.00 \pm 0.03$ keV
$kT_e = 207 \pm 9$ keV
$\tau = 0.18 \pm 0.02$
$F_{0.1-200\text{keV}} \approx 1.5 \times 10^{-8}$
ergs cm$^{-2}$ s$^{-1}$

ComPS (or CompTT, CompST) is a STATIC thermal Compt. model

Spectral steepening and higher cut-off in spectra

Higher $kT_e$ and lower $\tau$
Hot corona ($kT_e > 30$ keV)
Inner bulk region screened, high-energy spectrum is dominated by TC
Pure TC models good for spectral analysis

HARD STATE

Cool corona ($kT_e < 5$ keV)
Bulk comptonization of inner flow dominates over TC
Pure TC models provide misleading results

SOFT STATE

Strong Compton cooling by hotter disk photons
Presently there are no available physical models in XSPEC of bulk Comptonization for BH X-ray binary systems.

The reason is the difficulty of providing an analytical or numerical treatment for BH environment conditions (General Relativity, $V_{\text{free-fall}} \sim c$) easily implementable into a source code for XSPEC.

CompTB model in XSPEC was developed under Fokker-Planck approximation ($V_{\text{free-fall}} < c$) for NS. It can fit shape of BH spectra, but the parameters must be treated very carefully.

BMC is thus the best compromise: the general shape of the Green’s function (broken-PL) allows to apply the model to any spectral state.

The value of the GF index, and thus the spectral slope in different spectral states, is a matter of scientific debate.

Also, BMC provides information on the seed photon temperature and somewhat also on the system geometry through the illuminating factor $\log(A)$. 
The transition layer as the main site for the formation of fast temporal variability

The TL is defined by the region of the transition from the keplerian to the sub-keplerian regime

\[ \omega_R = \omega_{\text{ISCO}} \quad R = R_{\text{ISCO}} \]

\[ \omega_R = \omega_{\text{kepl}} = G M R_{\text{crit}}^{-3/2} \]

Energy release and hard X-rays production

\[ \frac{Q_{\text{cor}}}{\tau_0} \approx 20.2 \varepsilon(\tau) T_e(\tau) \]

- \( Q_{\text{cor}} \): energy flux released in TL
- \( \tau_0 \): TL - total optical depth
- \( T_e \): TL - electron temperature
- \( \varepsilon(\tau) \): TL - total energy density (erg cm\(^{-3}\))

Radial free-fall region

Non keplerian region

Keplerian disk: \( \omega_R = G M R^{-3/2} \)
The transition layer as the main site for the formation of fast temporal variability

\[
F(E) = \frac{C_n}{A+1} \left[ S(E) + A \times S(E) \times G(E, E_0) \right]
\]

As \( A \) increases the relative weight (Comptonization fraction) of HC dominates.
Log(A) vs RMS

Correlate the *A-parameter*, actually log(A) in BMC, with the RMS variability in the 3-60 keV

Very strong evidence that most of RMS variability originates in the TL
A peculiar difference between NS and BH systems

Only one spectral index $\Gamma$ characterizes the spectral state of BH sources

In BH sources the spectral index $\Gamma$ evolves as a function of the spectral state
Four different spectral states have been identified by Paizis et al. (2006) monitoring A sample of 12 LMXBs with INTEGRAL.
The evolution of the second index (PL component) of intermediate state NS sources cannot be studied because of statistics (only ON/OFF states detected).

However we can map the evolution of the first index (always present) both from a sample of sources in different spectral states (like an AGN-population study) or from a source evolving from soft to hard state.

In NS sources the TC spectral index $\Gamma$ remains stable around 2 as a function of the spectral state.
The importance of broad-band spectral coverage for mass determination using the scaling method

ST09 determined the mass of XTE J1859+226 using the scaling method in the $\Gamma$/QPO diagram and XTE J1550-564 as target source.

QPO centroid frequency is easier to be measured as it is model-independent.

Photon index $\Gamma$ of BMC was measured using a GAUSSIAN+BMC model and only PCA data (3-50 keV) of RXTE.

However, BeppoSAX analysis shows that actually a DISKBB+BMC or MODBB+BMC are best-fit models, GAUSSIAN+BMC does not work at all.

$$S_v = \frac{v_r}{v_t} = \frac{M_t}{M_r}$$

$$S_v = 0.696 \pm 0.015$$
New $\Gamma$/QPO diagram for RXTE using DISKBB+BMC model

Systematic shift to lower values of $\Gamma$ with DISKBB with respect to GAUSSIAN

$$S_\nu = 0.54 \pm 0.02$$

Would this imply that the mass of the BH is a factor about two lower than the value found by ST09?

$$M_{BH} = 4.2 \pm 0.6$$

The shape of the $\Gamma$/QPO diagram of XTE J1859+226 is model-dependent
However, also the spectrum of XTE J1550-564 was fitted by ST09 with a GAUSSIAN+BMC model

Newly fitting the spectrum with DISKBB+BMC

Similarly to XTEJ1859+226, systematic shift to lower values of $\Gamma$ with DISKBB instead of GAUSSIAN

$$S_\nu = 0.63 \pm 0.02$$

Thus a similar scaling factor is applied to the target and reference source when using the same spectral model
Conclusions

The joint BeppoSAX-RXTE observations of XTE J1859+226 are a typical example of how many physical informations can be obtained with simultaneous spectral and temporal analysis of sources.

We detected a spectral state of the source having some properties typical of the soft state ($F_{\text{disk}}/F_{\text{tot}} \sim 70\%$, RMS $\sim 5\%$) but with spectral index closer to the hard state ($\Gamma \sim 1.8$).

Found a new correlation between log(A) and RMS

- It goes in the same direction of $v_{QPO}$ vs RMS found by Casella et al. (2007)
- We expect this correlation holds in all BH sources
- Statistical limitation of RXTE when RMS $< 5\%$
- This limitation will be overcome by LOFT

Spectral modeling of fundamental importance in BH mass determination, in order to avoid bias.