# HARD TAIL DETECTION IN THE LMXB 4U 1636–53 FROM *INTEGRAL*

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## ABSTRACT

Recent *INTEGRAL* observations and archival *BeppoSAX* data have been analyzed to deeply investigate the hard X-ray behavior of the neutron star, atoll type, low mass X-ray Binary 4U 1636–53 . Our investigation in three different periods outline three corresponding different sates. In fact, the source was detected in both the canonical high and low state and moreover in one occasion *INTEGRAL* spectrum shows, for first time in this source, a hard tail dominating the emission above 30 keV. This spectrum is fitted as the sum of a Comptonized component similar to soft state and a power-law component ($\Gamma = 2.76$), indicating the presence of a non thermal electron distribution of velocities.

Key words: accretion, accretion disks – gamma rays: observations – radiation mechanisms: non-thermal – stars: individual: 4U 1636–53 – stars: neutron – X-rays: binaries.

## 1. INTRODUCTION

4U 1636–53 is a neutron star low mass X-ray binary (LMXB) classified as a atoll source [17], with an orbital period of 3.8 hr derived from the optical variability of its companion V801 Arae [25] and at distance of 3.7–6.5 kpc [15, 27, 2]. While the X-ray burst properties and timing signatures have been analyzed extensively (see [18], [4] and references therein) the spectral characteristics have been studied only at low energy with *Einstein* [6], *EXOSAT* [30], *Temna* [32] and *ASCA* [1]. In general, the spectrum was acceptably fitted by a Comptonization model plus a black body component. We report here a broad band spectral analysis performed on data from *BeppoSAX* and *INTEGRAL* satellites, which allowed us to better constrain the spectral parameters and to detect the presence of a high energy tail dominating the spectrum above $\sim 30$ keV. A similar feature has been observed in other LMXBs namely GX 17+2 [11], GX 349+2 [12], Sco X-1 [9], 4U 1608-522 [34], XB 1254-690 [20], Cir X-1 [21] and 4U 0614+091 [26].

## 2. OBSERVATIONS AND DATA ANALYSIS

Table 1 summarizes the log of *INTEGRAL* and *BeppoSAX* observations of 4U 1636–53 . *BeppoSAX* observed the source on three occasions: February and March 1998 and February 2000. LECS, MECS and PDS event files and spectra, available from the ASI Scientific Data Center, were generated by means of the Supervised Standard Science Analysis [14]. Both LECS and MECS spectra were accumulated in circular regions of 8' radius. The PDS spectra were obtained with the background rejection method based on fixed rise time thresholds. Publicly available matrices were used for all the instruments. Fits are performed in the following energy band: 0.5–3.5 keV for LECS, 1.5–10.0 keV for MECS and 15–70 keV for PDS.

The analyzed *INTEGRAL* [33] data set consists of all observations in which 4U 1636-53 was within the high-energy detectors field of view. Observations are organized into uninterrupted 2000 s long science pointing, windows (scw): light curves and spectra are extracted for each individual scw. Wideband spectra (from 5 to 150 keV) of the source are obtained using data from the two high-energy instruments JEM-X [23] and IBIS [29]. Data were processed using the Off-line Scientific Analysis (OSA version 5.1) software released by the *INTEGRAL* Scientific Data Centre. Data from the Fully Coded field of view only for both instrument have been used.

## 3. SPECTRAL ANALYSIS

Several physical models have been used to fit the whole data set, keeping the number of free parameters as low as possible. Each time a new component was added to the model, a F-test was performed. We assumed that a F probability larger than $95\%$ implies a significative improvement of the fit. The uncertainties are at $90\%$ confidence level for one parameter of interest ($\Delta\chi^2 = 2.71$). When spectra are from more than one detector, we allow the relative normalization to be free with respect to the MECS and IBIS data, for *BeppoSAX* and *INTEGRAL* respectively. XSPEC v. 11.3.1. has been used.

*Table 1. BeppoSAX and INTEGRAL Observations*

| BeppoSAX Journal | | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Start Date** | **Exposure time** | | | **Count s$^{-1}$** | | |
| | | LECS ksec | MECS ksec | PDS ksec | LECS [0.4-3 keV] | MECS [1.5-10 keV] | PDS [20-60 keV] |
| $1^{st}$ *epoch (a)* | 1998-02-24 | 13 | 39 | 17 | $14.66 \pm 0.03$ | $39.37 \pm 0.02^{a}$ | $0.48 \pm 0.04$ |
| $1^{st}$ *epoch (b)* | 1998-03-01 | 6 | 14 | 7 | $14.95 \pm 0.05$ | $25.42 \pm 0.04^{b}$ | $0.80 \pm 0.06$ |
| $1^{st}$ *epoch (c)* | 2000-02-15 | 12 | 37 | 19 | $22.08 \pm 0.04$ | $29.09 \pm 0.03^{b}$ | $0.73 \pm 0.03$ |

| INTEGRAL Journal | | | | | |
|---|---|---|---|---|---|
| | **Start Date** | **Exposure time** | | **Count s$^{-1}$** | |
| | | JEM-X ksec | IBIS ksec | JEM-X [5-15keV] | IBIS [20-150 keV] |
| $2^{nd}$ *epoch* | 2003-03-04 | 36 | 594 | $6.3 \pm 0.2$ | $10.74 \pm 0.08$ |
| $3^{rd}$ *epoch* | 2003-03-04 | 16 | 117 | $3.70 \pm 0.06$ | $3.22 \pm 0.04$ |

[a] MECS count rates refer to MECS2 and MECS3 units. [b] MECS count rates refer to only MECS2 unit.

Spectral behavior has been studied separately in three epochs consisting of the following data:

- $1^{st}$ *epoch*: all three *BeppoSAX* observations available from February 1998 to February 2000. During these periods the source was always in a soft/high state.
- $2^{nd}$ *epoch*: JEM-X and IBIS data available from 52644 MJD to 53644 MJD with count rate $< 5\ counts\ s^{-1}$ in the 20–40 keV energy band. For the chosen period the source was in a hard/low state.
- $3^{rd}$ *epoch*: JEM-X and IBIS data available from 52644 MJD to 53644 MJD with count rate $> 5\ counts\ s^{-1}$ in the 20–40 keV energy band. This epoch does not corrspond to either the soft or the hard state and and here we call it *peculiar* state as will be explained in detail later on.

After veryfing there were no changes in the three observations and in order to achieve the highest signal to noise ratio, we build the *BeppoSAX* average spectrum arranging all three observations. We then can take advantage of the high quality of the average spectrum up to about 70 keV. The most simple model which provides a good fit to the average *BeppoSAX* spectrum in the energy band 0.5–70 keV consist of a thermal Comptonized component modeled in XSPEC by COMPTT (a spherical geometry was assumed) plus a soft component which we modeled with two temperature blackbody. Being the column density $N_{\rm H}$ towards the source measured by the LECS and MECS instrument always close to the galactic column density ($N_{\rm H}\ galactic\ =\ 3.58 \times 10^{21}\ cm^{-2}$, estimated from the 21 cm measurement [10]), we fix this parameter at this value. Spectral fit results are given in Table 2, the average spectrum is shown in Fig. 1.

The source was in the soft/high state with an un-absorbed luminosity of $L_{0.1-200\,\rm keV} \simeq 2.0 \times 10^{37}$ erg s$^{-1}$, assuming a distance of 5.9 kpc (Cornelisse et al. 2003). As in the case of the *Einstein* observation [6], thermal Comptonization of the optically thick plasma corona with a quite low electron temperature is dominating.

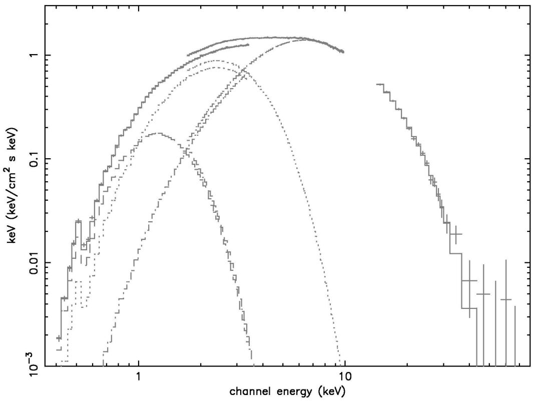


*Figure 1. The BeppoSAX average spectrum in the soft state (epochs 1), shown together with the total model and its components: the total, two blackbody and the Comptonization components.*

The most simple model which provides a good fit to the *INTEGRAL* hard state consist of a thermal Comptonized component modeled in XSPEC by COMPTT [28] (a spherical geometry was assumed) plus a soft component which we modeled by a single temperature blackbody. Because of the very good low energy *BeppoSAX* coverage, we used the average value of input soft photon temperature and column density ($T_0 = 1.3 keV$ and $N_H = N_H\ Galactic$) measured by the BeppoSAX observations. During this period, the source has a luminosity of $L_{0.1-200\,\rm keV} \simeq 1.4 \times 10^{37}$ erg s$^{-1}$, lower than the one in the soft state, in agreement with the usual ranking of the luminosity in atoll sources (e.g., [17]; [31]; [16]). The electron temperature is now substantially higher than in the soft state, $T_{\rm e} \sim 23$ keV, and the Comptonization component extends well above $\sim\ 100$ keV. The same model was been applied to the $2^{nd}$ *INTEGRAL* data set but resulted in a poor fit with a $\chi^2/d.o.f = 97/57$ with clear residuals above 60 keV. Adding a power law improves the fit significantly ($\chi^2/d.o.f$ becomes $64/55$). The disk component becomes negligible and it is not necessary to best fit the data. Spectral fit results are given in Table 2, and spectra are shown in Fig. 2. Since the spectral parameters in the *peculiar* state are similar to

*Table 2. Results of the fit of 4U 1636–53 spectra in the energy band $0.5 - 70$ keV and $5 - 150$ keV for BeppoSAX and INTEGRAL observations respectively, for three different spectral states.*

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **BeppoSAX average high/soft state spectrum** | | | | | | | | |
| $model = bbody + bbody + comptt$ | | | | | | | | |
| $\mathrm{T_{BB1}}$ *keV* | $\mathrm{T_{BB2}}$ *keV* | $T_0$ *keV* | $\mathrm{T_e}$ *keV* | $\tau$ | $R_{\mathrm{BB1}}$ km | $R_{\mathrm{BB2}}$ km | $n_{\mathrm{COMPTT}}$ | $\chi^2$/d.o.f |
| $0.24 \pm 0.01$ | $0.58 \pm 0.02$ | $1.3 \pm 0.1$ | $3.4 \pm 0.3$ | $3.8 \pm 0.4$ | $79 \pm 6$ | $25 \pm 1$ | $0.19 \pm 0.02$ | 235/190 |
| **INTEGRAL low/hard state spectrum** | | | | | | | | |
| $model = bbody + comptt$ | | | | | | | | |
| | $\mathrm{T_{BB2}}$ *keV* | $T_0$ *keV* | $\mathrm{T_e}$ *keV* | $\tau$ | $R_{\mathrm{BB2}}$ km | $n_{\mathrm{COMPTT}}$ $10^{-2}$ | $\chi^2$/d.o.f | |
| | $1.2^{+0.2}_{-0.3}$ | 1.3 fixed | $23^{+7}_{-2}$ | $1.1^{+0.5}_{-0.3}$ | $5^{+3}_{-2}$ | $1.0^{+0.3}_{-0.1}$ | 57/59 | |
| **INTEGRAL peculiar state spectrum** | | | | | | | | |
| $model = comptt + powerlaw$ | | | | | | | | |
| | $T_0$ *keV* | $\mathrm{T_e}$ *keV* | $\tau$ | $\Gamma$ | $n_{\mathrm{COMPTT}}$ $10^{-2}$ | $n_{\mathrm{powerlaw}}$ $ph\ keV^{-1}\ cm^{-2}$ | $\chi^2$/d.o.f | |
| | 1.3 fixed | $5^{+4}_{-3}$ | $3 \pm 2$ | $2.6 \pm 0.1$ | $2.8^{+0.8}_{-0.6}$ | $1.0^{+1.4}_{-0.5}$ | 72/57 | |

those in the soft/high *BeppoSAX* state, a possible interpretation of this state is that 4U 1636–53 was in a similar soft/high state as during the *BeppoSAX* observations, but with a new overlapped component at high energies simultaneously present. The un-absorbed luminosity is $L_{0.1-200\,\mathrm{keV}} \simeq 7.4 \times 10^{37}$ erg s$^{-1}$.

## 4. CONCLUSIONS

The black-body component in the soft states could originate at both the neutron star surface and the surface of an optically-thick accretion disk. In our observations the two black body components seems to originate from two different parts of the disk, corresponding to two different temperature. The Comptonization component may arise from a corona above the disk and/or between the disk and the neutron star surface. In the hard states, accretion probably assumes the form of a truncated outer accretion disk as previously reported by [3] for LMXB 4U 1705-44. The spectral transitions are generally, but not necessarily, coupled with changes in luminosity, indicating they are driven by variability of the accretion rate or change of the geometry of the system as for Black Hole hard/soft transition at constant luminosity [4]. For 4U 1636–53 the accretion rate is lower in the hard state than in the soft state and becames very high in the *peculiar* state. We note this value can be influenced by the steep power law that dominates the energy spectrum at low energies. The emission is best described by Comptonization from a complex electron distribution due to a low temperature ($\sim$ 5keV) thermal electron distribution together with non-thermal power-law electrons. This two-component electron distribution could be explained by the following hypothesis:

- Non-thermal electron acceleration regions powered by magnetic reconnections above a disc. Low-energy electrons cool preferentially by Coulomb collisions leading to a thermal distribution while the

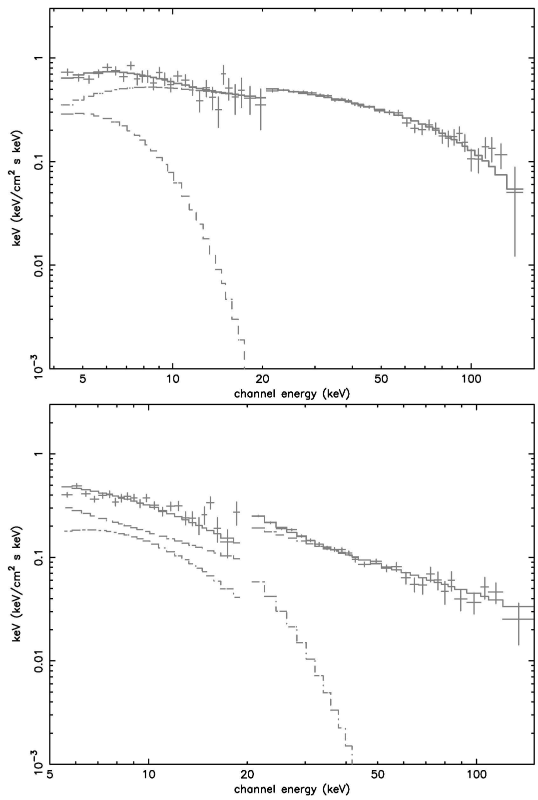


*Figure 2. The spectra of epochs 2 (soft state, top) and 3 (peculiar state, bottom) observed by INTEGRAL , shown together with the total model and its components.*

high-energy electrons cool by Compton scattering, preserving a non-thermal distribution [7].

- The magnetic reconnection above the disc can produce a non-thermal electron distribution, while overheating of the inner disc produces the thermal Comptonization [19].
- The power-law component could be produced by Componization by synchrotron emission in the jet [5, 13] In our source, this hypothesis is strengthened by radio detection: Sydney University Molonglo Sky Survey catalog gives a flux of 7.5 mJy at 843 GHz [24].

Finally, Laurent & Titarchuk [22] suggest the detection of a power-law component at high energy to be a signature of presence black hole in an X-ray binary system. Data extended up to a few hundred keV are need to check this criterion proposed to distinguish black hole versus neutron star binaries.

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