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HYBRID MODELIZATION OF THE HIGH-ENERGY BROAD-BAND SPECTRA OF CYGNUS X-1 OBSERVED BY INTEGRAL

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Abstract. We report high-energy spectral results on Cygnus X-1 obtained with *INTEGRAL* which extensively observed this confirmed black hole from 2002 November to 2004, collecting a total of 1.5 Ms of data. We compare the spectral properties of the source in three distinct observed spectral states (hard, soft and intermediate) over the 5 keV–1 MeV energy range. Spectral changes in the hard and soft components occur together with Fe line and reflection evolutions. Our results give new insights on the physical changes that took place in the system (disc and corona) at almost constant luminosity during spectral transitions. In particular, we observed in 2003 June a high-energy tail at several hundred keV in excess of the thermal Comptonization model suggesting the presence of an additional non-thermal component.

1 Introduction

Galactic Black Holes (BH) X-ray binary systems display high-energy emissions characterized by spectral and flux variabilities (from milliseconds to months). These systems are found in several spectral states (McClintock & Remillard 2006) giving us the possibility to study the physical properties of emitting regions (disc, corona, jets) and their evolutions. The two main states are the Thermal Dominant State (TDS) and the Low/Hard State (LHS) characterized by different combinations of soft (multicolor black-body coming from an optically thick and geometrically thin accretion disc), hard (power law, with a possible break at 50–100 keV) and reflection (continuum excess, fluorescence lines and K-edge) spectral components coupled to various properties of variabilities in the power spectrum (e.g., Belloni 2005) and to radio changes (e.g., Corbel et al. 2003). Other states have been identified characterized either by an even greater luminosity than in the TDS (the Steep Power law State) or by variability and X-ray spectral properties mostly intermediate between the LHS and the TDS: the Intermediate State (IS).

Cygnus X-1/HDE 226868 is one of the first X-ray binaries detected. Among the brightest X-ray sources of the sky, it is also very variable on different time scales and it ranks among the microquasars with a relativistic jet detected (Stirling et al. 2001). Since its discovery in 1964 by Bowyer et al. (1965), it has been extensively observed as the prototype of BH candidates in radio/optical wavelengths and with all high-energy instruments, from soft X-rays to γ-rays (e.g., *ASCA*, SIGMA, *RXTE*, *BeppoSAX*, *CGRO* and *INTEGRAL*). This persistent source located at 2.4 ± 0.5 kpc (McClintock & Remillard 2006) accretes via a strong stellar wind coming from its giant companion.

The mass function constrains the inclination angle of the system between 25° and 67° (we adopted the value of 45°). Cygnus X-1 spends most of its time (70%) in the LHS. During 1996 June, in addition to the dominant black body component and the hard component, a high-energy tail extending up to 10 MeV was discovered (McConnell et al. 2002). We report exciting results collected on Cygnus X-1 over two years with *INTEGRAL* (e.g., Cadolle Bel et al. 2006, hereafter CB06; Malzac et al. 2006), fully exploiting the broad-band capability of all high-energy instruments on board.

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2 Observations and Data Reduction

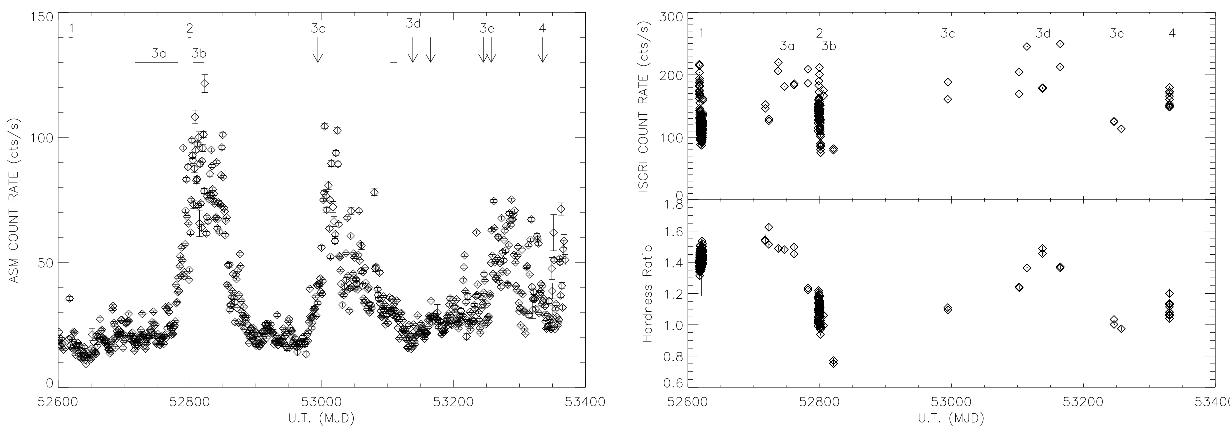

Fig. 1. *Left:* *RXTE*/ASM daily average (1.5–12 keV) light curve of Cygnus X-1 from 2002 November to 2004 November (MJD = JD - 2 400 000.5) with the period of our *INTEGRAL* observations (see text and Table 1 for epoch definitions). *Right:* The 20–200 keV IBIS/ISGRI light curve of Cygnus X-1 during the same periods (top) and corresponding hardness ratio (bottom) between the 40–100 keV and 20–30 keV energy bands

The periods of our *INTEGRAL* observations (epochs 1 to 4 defined in the first column of Table 1) are indicated on Fig. 1 (left) simultaneously to the *RXTE*/ASM light curve. To discuss the time evolution of the source, IBIS/ISGRI light curves and Hardness Ratios (HR) obtained over two years are reported in Fig. 1 (right). Epoch 1 (2002 December 9–11) includes part of the PV-Phase observations of Cygnus X-1. Epoch 2 corresponds to an Open Time observation performed on 2003 June 7–11 while epochs 3 and 4 refer respectively to the set of Cygnus X-1 observations during the GPS and the 2004 November calibrations. We reduced the JEM-X, IBIS and SPI data with the standard analysis procedures of `OSA 5` following the methods described in CB06.

3 Spectral results

As shown in Fig. 1 (left), during the epoch 2 *INTEGRAL* observations, the 1.5–12 keV ASM average count rate of Cygnus X-1 ($\sim$ 1.3 Crab) was larger than during epoch 1 ($\sim$ 290 mCrab) by a factor of 4.5. The derived IBIS/ISGRI 20–200 keV light curves and HR of Cygnus X-1 are shown in Fig. 1 (right, epochs 1 to 4). From epoch 1 to epoch 2, while the ASM average count rate increased, the 20–200 keV IBIS/ISGRI one decreased from $\sim$ 910 to $\sim$ 670 mCrab. This probably indicates a state transition as also suggested by the decrease in the IBIS HR (the source softens). Similar transitions, with a change in the ASM light curves and an evolving IBIS HR, occurred again during epoch 3 and epoch 4. Table 1 gives all the best-fit parameters of Cygnus X-1 with the thermal Comptonization model of Titarchuk (1994) and, when needed (see our approach described in CB06), a multicolor black body disc (Mitsuda et al. 1984), reflection (Magdziarz & Zdziarksi 1995) and Fe line components.

3.1 The LHS spectrum

Fig. 2 (left) shows the resultant $EF(E)$ spectrum and its best-fit with the JEM-X, IBIS and SPI data. The best-fit model reported in Table 1 includes thermal Comptonization convolved by reflection with solar abundances for Fe and He. We obtain a plasma temperature $kT_{\rm e}$ of 67 keV with an optical depth τ of 1.98 and $\Omega/2\pi = 0.25$, with $\chi^2_{red} = 1.45$ (230 dof). The disc black body is very weak or below the energy range of JEM-X: this component was not used in our fits. As it gives no contribution, we froze the kT_0 temperature of COMPTT at 0.20 keV. While the 20–100 keV luminosity is 6.5×10^{36} ergs s^{-1} (at 2.4 kpc), the bolometric luminosity

Table 1. Best-fit parameters of Cygnus X-1 for the current thermal model in the several observation epochs.

Epochs, dates (MJD)	Disc Norm.[a]	$kT_{\rm in}$ or kT_0 (keV)	$kT_{\rm e}$ (keV)	τ	$E_{\rm Fe}$ line (keV)	$\Omega/2\pi$[b]	χ^2_{red} (dof)
1, 52617-620	-	0.20 (frozen)	$67\,^{+\,8}_{-\,6}$	$1.98\,^{+0.21}_{-0.23}$	-	$0.25\,^{+0.03}_{-0.04}$	1.45 (230)
2, 52797-801	$250\,^{+89}_{-59}$	1.16 ± 0.07	$100\,^{+29}_{-17}$	$0.98\,^{+0.25}_{-0.28}$	$7.07\,^{+0.12}_{-0.11}$	$0.57\,^{+0.09}_{-0.06}$	1.69 (236)
3a, 52710-780	-	0.20 (frozen)	$68\,^{+22}_{-12}$	$2.08\,^{+0.51}_{-0.84}$	6.48 ± 0.13	$0.32\,^{+0.05}_{-0.07}$	1.07 (190)
3b, 52801-825	$312\,^{+25}_{-24}$	1.15 ± 0.03	93 ± 42	$0.80\,^{+0.86}_{-0.40}$	6.40 ± 0.73	$0.58\,^{+0.20}_{-0.18}$	0.93 (190)
3c, 52990	$361\,^{+61}_{-67}$	0.99 ± 0.08	$58\,^{+54}_{-15}$	$1.60\,^{+0.64}_{-0.80}$	6.96 ± 0.19	$0.23\,^{+0.17}_{-0.09}$	0.99 (190)
3d, 53101-165	-	0.20 (frozen)	$56\,^{+12}_{-\,7}$	$2.28\,^{+0.30}_{-0.41}$	6.11 ± 0.26	0.27 ± 0.06	0.81 (190)
3e, 53240-260	132 ± 10	1.39 ± 0.77	$48\,^{+20}_{-\,6}$	$1.85\,^{+0.40}_{-0.07}$	6.49 ± 0.38	$0.49\,^{+0.37}_{-0.32}$	1.56 (190)
4, 53335	$232\,^{+21}_{-32}$	1.16 (frozen)	$128\,^{+84}_{-63}$	$0.74\,^{+0.88}_{-0.38}$	$7.78\,^{+0.44}_{-0.42}$	$0.47\,^{+0.18}_{-0.14}$	0.97 (221)

Notes:
a) Disc normalization $K = (R/D)^2 \cos\theta$ (R: inner disc radius in units of km; D: distance to the source in units of 10 kpc; θ: inclination angle of the disc).
b) Solid angle of the reflection component.
Model in XSPEC notations: CONSTANT*WABS*(DISKBB+GAUSSIAN+REFLECT*COMPTT) with $N_{\rm H}$=6 × 10^{21}cm^{-2} and kT_0 value tied to disc $kT_{\rm in}$. Errors are at 90% confidence level ($\Delta\chi^2 = 2.7$).

(extrapolated from 0.01 keV to 10 MeV) has the value of 2.2 × 10^{37} ergs s^{-1}. The best-fit parameters we obtain are consistent with those found in BH binaries in the LHS as fully discussed in CB06.

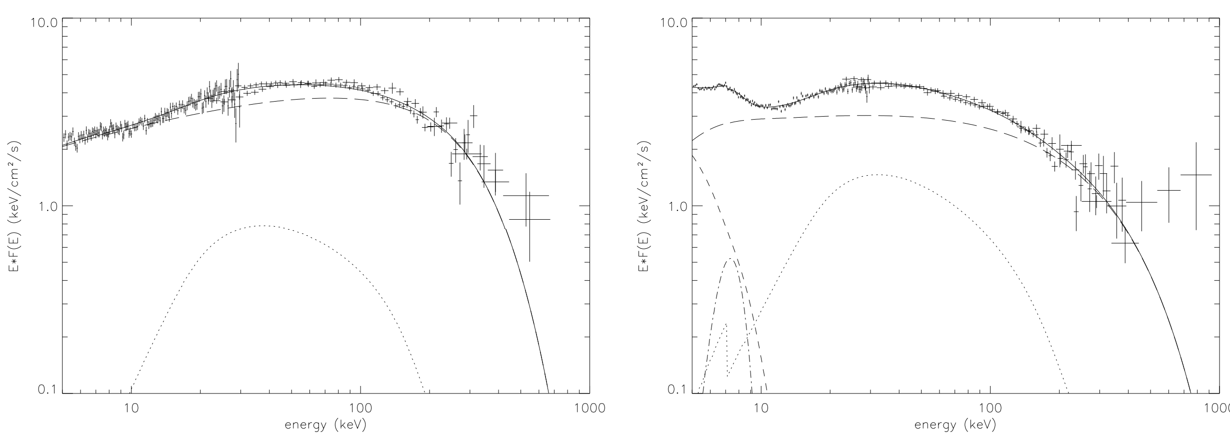

Fig. 2. *Left:* Epoch 1 unabsorbed $EF(E)$ spectrum of Cygnus X-1 along with the best-fit model described in Table 1 with the JEM-X, SPI and IBIS (ISGRI and PICsIT) data. *Right:* The same for epoch 2. *Dotted*: reflection. *Long dashes*: Comptonization. *Dashed*: disc. *Dotted-dashed*: gaussian line. *Thick*: total model.

3.2 The transition to a softer state in 2003 June

Fig. 2 (right) shows the resultant $EF(E)$ spectrum and its best-fit with the JEM-X, IBIS and SPI data. Table 1 summarizes the best-fit parameters and the χ^2_{red} obtained from 5 keV up to 1 MeV. We get a plasma temperature $kT_{\rm e}$ of 100 $^{+29}_{-17}$ keV and an optical depth τ of 0.98 $^{+0.25}_{-0.28}$, respectively higher and lower than in epoch 1. The inner disc temperature reached 1.16 keV and a significant line is detected at a centroid energy of 7.07 keV, with an Equivalent Width (EW) of 1.4 keV. With 2.4 kpc, the luminosity is 6.5 × 10^{36} ergs s^{-1} in the 0.5–10 keV range and 5.2 × 10^{36} ergs s^{-1} in the 20–100 keV band. The bolometric (extrapolated) luminosity has the value of 2.0 × 10^{37} ergs s^{-1}; the disc accounts for 26 % of the total luminosity (its normalization is possibly underestimated as the data start at 5 keV) and the reflection is higher in epoch 2 than in epoch 1.

Considering the behavior of the ASM, IBIS light curves and HR (Fig.1), the relative softness of the spectrum and the presence of a relatively strong hard energy emission, it appears that during the 2003 June observations Cygnus X-1 was in the IS. This is also confirmed by radio observations of Malzac et al. (2006) who suggested that the fluctuations of the radio luminosity were associated with a pivoting of the high-energy spectrum and that the source did not display the usual radio/X-ray correlation. The derived thermal Comptonization parameters are consistent with those found in BH binaries in soft states (McClintock & Remillard 2006).

As it can be seen in Fig. 2 (right), an excess with respect to the Comptonized spectrum above 400 keV is observed in the SPI data (not present in epoch 1 and not due to instrumental effects). Consequently, to account for this high-energy emission, we fitted the data with the hybrid model of Coppi (1999) coupled to the usual disc and Fe line components. This model combines both thermal and non-thermal corona particle distributions in the calculation of the emergent spectrum. Fig.3 shows the resultant count spectrum obtained in epoch 2 with this model: with a $\chi^2_{red} = 1.55$ (232 dof), clearly better than the current epoch 2 thermal model, the derived thermal values of τ, $\Omega/2\pi$, $E_{\rm Fe}$ centroid and EW match, within the uncertainties, the parameters obtained in Table 1. The value of $kT_{\rm e}$ (equals to 42 keV) decreases from the pure thermal model as expected. We found a power law spectral index of 2.4 for non-thermal electrons which power represents $\sim 16\%$ of the total power supplied to the electrons in the corona. The inferred luminosity in the 20–100 keV range is 6×10^{36} ergs s^{-1} while the bolometric one is 3.3×10^{37} ergs s^{-1}.

We sampled epoch 3 in five distinct sub-groups (noted a to e) of close pointings which appear to occur, according to Fig. 1, in different regimes of ASM count rate and of average IBIS HR. The best-fit spectral results we obtained indicate that, during sub-groups 3a and d, Cygnus X-1 was in a LHS (as in epoch 1) while, in sub-groups 3b, c and e and in epoch 4, the source was in a softer state.

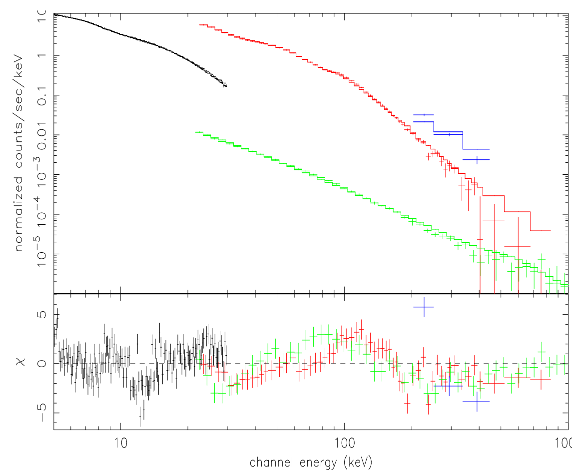

Fig. 3. Spectra of Cygnus X-1 during epoch 2 with JEM-X (black), SPI (green) and IBIS (ISGRI: red; PICsIT: blue) along with the best-fit hybrid model of Coppi (1999) including a non-thermal distribution for corona particles. Residuals in σ units are also shown.

4 Discussion

Using the broad-band capability of *INTEGRAL*, it has been possible to accumulate a large amount of simultaneous data on Cygnus X-1 between 5 keV–1 MeV to follow its spectral evolution from 2002 to 2004. We characterized Comptonization parameters changes of the source correlated to the presence of a variable disc emission indicating transitions between the LHS and softer (Intermediate) states. Besides, a high-energy tail during the IS emerged from pure Comptonization between 400 keV–1 MeV and was probably associated with a non-thermal component. The extent to which the spectrum hardens at energies approaching 1 MeV has now become an important issue for theoretical modelling of the accretion processes and radiation mechanisms in BH binaries. We hope to further investigate this using *INTEGRAL* data from this source and other bright BH X-ray binaries.

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