EPJ Web of Conferences **61**, 03006 (2013)
DOI: 10.1051/epjconf/20136103006

The high-energy spectrum of Cygnus X–1: corona and jet contributions

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Abstract. We have analyzed six years of *INTEGRAL* observations of the BH binary Cygnus X-1. We report on the evolution of the physical parameters of the accretion flow across spectral transitions. In particular, we have used for the first time the new model BELM which gives constraints on the intensity of the magnetic field in the X-ray corona of BH binaries. We have found that in the softer states, the magnetic field is at most of the order of 1E+06 G. In the harder states, if the non-thermal excess observed above a few hundred keV is produced in the same region as the bulk of the thermal Comptonization, the upper limit on the magnetic field is about 1E+05 G. On the other hand, as suggested by the recent polarization measurements, this high-energy excess may be produced in the jet: in this case the constraints on the magnetic field in the hard state are somewhat relaxed and the upper limit rises to 1E+07 G.

1 Introduction

In the simplest classification, Black Hole binaries (BHBs), and in particular Cyg X-1, are observed in two main spectral states: the hard state (HS) with a X/γ spectrum believed to originate from thermal Comptonization in a hot electrons dominated cloud (the so-called *corona*); the soft state (SS) showing a prominent ~1 keV black-body associated with the optically thick accretion disc plus a power-law tail, usually explained as Comptonization by a non-thermal electrons distribution. Although the scattering electrons have a predominantly Maxwellian energy distribution in the HS, there are indications that the electron distribution may have some high-energy tail i.e., it is hybrid, thermal/non-thermal. The different electron distributions in the hard (HS) and soft (SS) spectral states of BHBs could be caused by kinetic processes and changing because of varying physical conditions in the corona (Malzac & Belmont 2009, MB09; Poutanen & Vurm 2009, PV09). In presence of a magnetic field in the corona, the electron distribution can appear thermal, even when acceleration mechanisms would produce non thermal distributions. This is due to fast and efficient thermalization through synchrotron self-absorption as first pointed out by Ghisellini et al. (1988). MB09 have presented a rough 'fit by eye' of the average *CGRO* data of Cyg X-1 with the new model BELM [1], providing estimates of the magnetic field in the hard state under the assumption that the non-thermal excess is produced by electrons in the same zone as the Maxwellian component. In Del Santo et al. (2013) we used this model on *INTEGRAL* data. We performed a statistical fit of the whole range of observed spectral shapes and also considering the possibility that the non-thermal excess in the hard state may have a different origin than the corona. For the first time, we set quantitative constraints on the strength of the magnetic field in the corona of Cygnus X-1.

2 Modeling high-energy spectra of Cyg X-1: EQPAIR and BELM

We have analyzed 6 years of observations of Cyg X-1 with the *INTEGRAL* observatory and produced 12 high-quality, stacked broad-band (3-800 keV) hard X-ray spectra representative of the whole range of spectral shapes observed in this source. We have studied these spectra by fitting them with two different Comptonization models, namely EQPAIR [2] and BELM [1]. This allowed us to constrain the physical conditions in the corona and disc and determine how the physical parameters change during the spectral evolution (see Fig. 1).

Details on the models, spectral analysis variability study and results are reported in [3]; here, we only summarize and discuss few results. We point out that for the first study we used BELM assuming a Synchrotron Self Compton (SSC) emission and pure non-thermal acceleration; we did not include any thermal or Coulomb heating.

The differences between the two models EQPAIR and BELM can be briefly summarized as follow:

- in the first model, there is no magnetic field in the corona considered while in BELM the magnetic field B is taken into account and expressed by the magnetic compactness $l_B \propto B^2$;
- in EQPAIR the Comptonizing electrons population is hybrid thermal (Maxwellian) and non-thermal (Γ_{inj} the power-law index of the electrons distribution), while in

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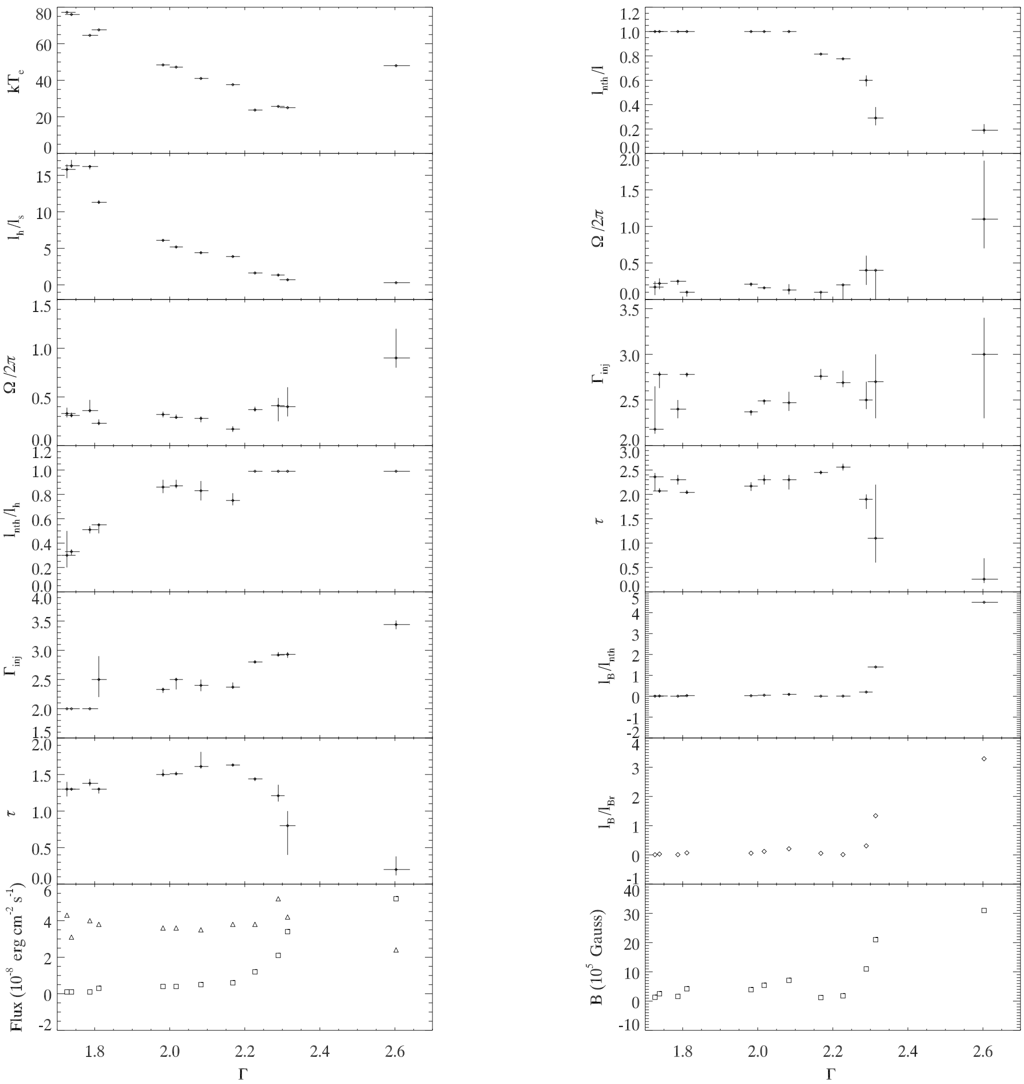

Figure 1. EQPAIR (*Left*) and BELM (*Right*) spectral parameters reported in [3] (Tab. 3 and 4, respectively) vs the Γ slope of the IBIS/ISGRI spectra fit with a simple power law in the range 30–100 keV.

BELM there is only one population of non-thermal electrons injected with Γ_{inj} and then thermalized via Synchrotron boiler;

- seed photons in EQPAIR come from the thin accretion disc while in BELM are due to both synchrotron radiation and disc photons.

We have obtained few common results. The main ones can be summarized as follow (see Fig. 1):

- a gradual decreasing (up to 0.2 in SS) of the Thomson depth of the corona is observed. Could be it due to the gradual condensation of the corona into the disc?
- the observed value of $\tau > 1$ in hard states does not reproduce ADAF models. We noted that elaboration of ADAF models [10] may reproduce the high tau observed. However these models require high values of B. This is discussed in Section 3.
- Dramatic variation of the thermal disc flux (of a factor of 50), low electron temperature (kT$_e$) observed in soft states combined with Comptonized component almost constant (a factor of 2) bring us to the conclusion that spectral transitions are driven by the soft cooling. This was also observed by us in the transient BH GX 339-4 [4].

3 BELM and magnetic field results

Here we show four spectra of Cyg X-1 in different spectral states fit by BELM (see Fig. 2). We have observed that in the soft state photons from the accretion disc represent the main source of soft seed photons (see Fig. 3). On the other hand, in the HS the synchrotron photons may dominate. It is therefore likely that both the accretion disc and the magnetic field contribute to seed the Comptonization process. It is interesting to express the magnetic field compactness as a fraction of the equipartition compactness:

$$l_{B_R} \simeq \frac{3l}{4\pi}(1 + \frac{\tau_T}{3}). \qquad (1)$$

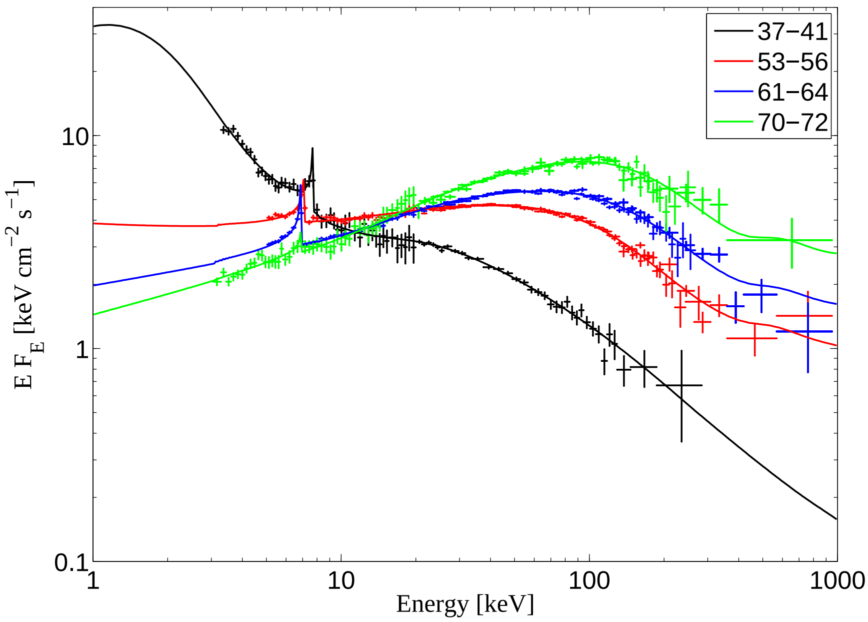

Figure 2. Joint JEM-X, IBIS and SPI energy spectra of Cyg X-1 during four different spectral states fitted with the BELM model with pure non-thermal acceleration plus DISKLINE and REFLECT (see [3]).

This ratio is independent of the uncertainties on the source size and distance. We found that in the hard state the upper limit on the magnetic field is B~ 10^5 G and these magnetic fields are strongly sub-equipartition (see Tab. 4 in Del Santo et al 2013): we concluded that B cannot power the corona. On the other hand, we observed that in soft states B is super-equipartition and of the order of B~ 10^6 G which is consistent with the corona powered by the magnetic energy. These results are in agreement with qualitative results of PV09 (with a different code) and MB09, as well as consistent with analytic estimation of Wardzinski & Zdziarski (2001) performed on the hard state of GX 339–4. This demonstrate that our results are not model dependent.

3.1 May the high energy emission above 200 keV come from different regions than the corona?

We have also studied the case that the tail observed in the hard states is not produced in the same region as the bulk of the thermal Comptonization, but somewhere else (jet? [7, 14] another corona region? [9]). We were motivated by the polarization measurements of the hard X-ray emission of Cyg X-1 performed with *INTEGRAL*, independently obtained with the two telescopes IBIS [7] and SPI [6], Laurent et al. (2011) found that, while the 250–400 keV spectrum is consistent with emission dominated by Compton scattering by thermal electrons and are weakly polarized (Pf < 20%), the second spectral component seen in the 400 keV–2 MeV band is strongly polarized (Pf = 67± 30%). They have argued that the MeV excess is likely to be produced in jet through synchrotron emission in a very coherent magnetic field. Such a high degree of polarization is indeed difficult to achieve through inverse Compton emission in the corona. Jourdain et al. (2012) reported on a similar result by using the SPI telescope. They found that above 230 keV the Cyg X-1 emission is indeed polarized, with a mean polarization fraction of 76± 15%.

To investigate this issue, we computed a new table model with pure Coulomb heating, since the hard spectra below the cutoff (about 200 keV) could also be reproduced by SSC models with pure thermal heating. In this case the exact heating mechanism is of little importance for spectral modeling, because whatever the heating mechanism the resulting electron distribution is very close to a pure Maxwellian. In BELM this electron thermal heating mechanism is assumed to be Coulomb collisions with a distribution of hot thermal protons [8]. Then, the constraints on the magnetic field are expected to be different.

As expected, the broadband spectrum can not be fitted with this pure thermal model, since it does not reproduce the highest energy data (above 200 keV), which either requires a significant level of non-thermal acceleration or must originate in a different region. When excluding data above 200 keV, we obtained good fits (see Tab. 5 in [3]).

Thus, by assuming that the highest energy emission originates from a different region, we obtain that the magnetic field in the hard states is stronger by a factor of 100 compared to that estimated in the SSC model. The magnetic field is now allowed to be strongly super equipartition ($l_B/l_{Br} \gg 1$) with typical upper limits of the order of 10^7 G. In this case B is consistent with the magnetically dominated hot accretion flow model of [10, 11] which also produces the rather large Thomson depths observed.

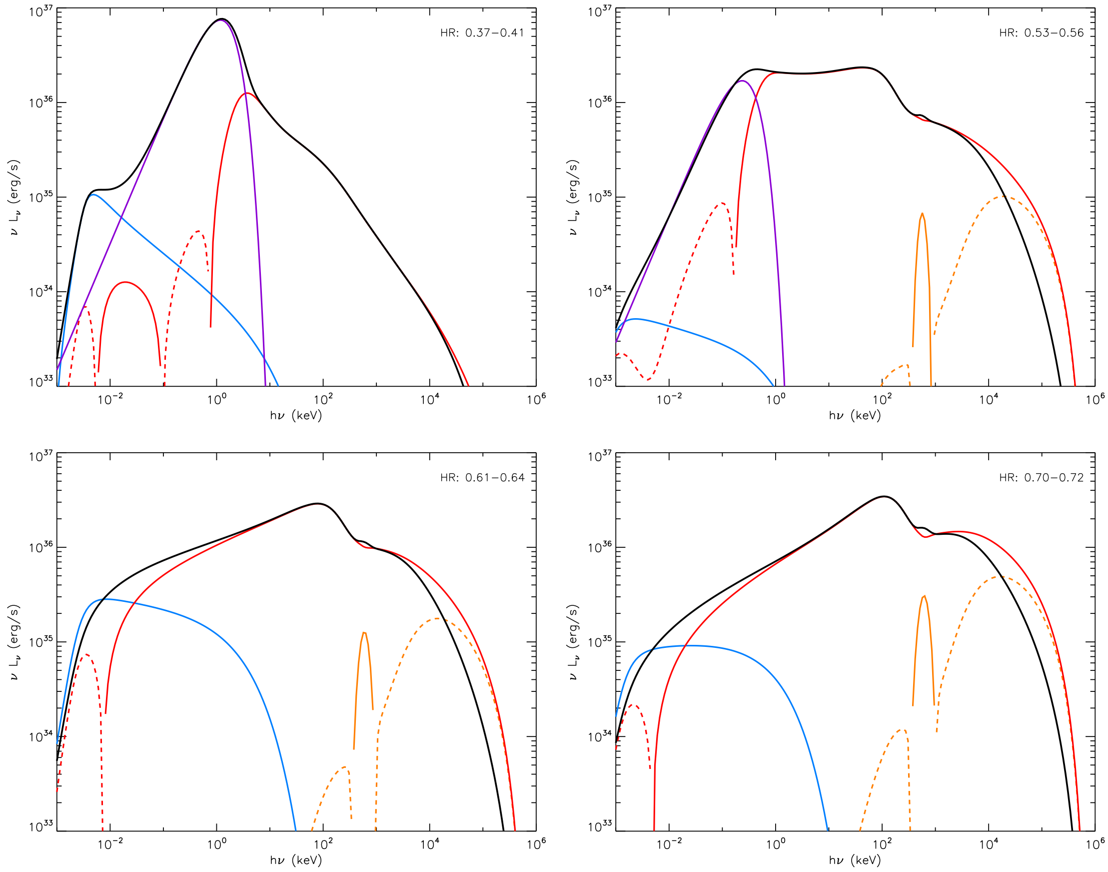

Figure 3. BELM total models (black) corresponding to fits of the four spectra shown in Fig. 2 and the components: Compton (red), pair annihilation/production (orange), synchrotron (blue), soft black body photons (purple). Solid lines correspond to positive contribution to the spectrum, dashed lines correspond to negative contribution.

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