SF2A 2015
F. Martins, S. Boissier, V. Buat, L. Cambrésy and P. Petit (eds)

A STUDY OF THE CYG X-1 SPECTRAL COMPONENTS IN RADIO, X, AND γ-RAYS: HIGH ENERGY POLARIMETRY, SPECTROSCOPY, AND THE RELATION WITH THE SPECTRAL STATE

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Abstract. We present an analysis of AMI-Ryle (15 GHz) and INTEGRAL (0.01–2 MeV) observations of Cygnus X-1 performed between early 2003 and late 2012. The observations are separated into distinct spectral states thanks to a model-independent approach based on data acquired with All Sky Monitors. The multi-wavelength state-dependent properties of the source are then studied: a compact radio jet is detected in the hard and intermediate states and is absent in the soft state. We clearly detect a high energy tail dominating the 0.4–2 MeV emission in the hard state. This component is highly polarized and we suggest it to be the signature of jet emission at high energies.

Keywords: accretion, accretion disks, black hole physics, stars: individual (Cyg X-1), X-ray binaries, radio observations, X-ray observations, polarimetry

1 Introduction

The black hole binary (BHB) Cygnus X-1 (Cyg X-1) was the first Galactic source thought to host a black hole hole (Bolton 1975). Recent estimates led to a black hole mass of $\mathrm{M_{BH}} = 14.8 \pm 1.0\,\mathrm{M_\odot}$ (Orosz et al. 2011). The donor star is HDE 226868 (Bolton 1972; Walborn 1973) an O supergiant star. This system is located at a distance of $d = 1.86 \pm 0.12\,\mathrm{kpc}$ from Earth (Reid et al. 2011; Xiang et al. 2011), making it one of the closest BHBs known so far.

Although Cyg X-1 has a high mass companion, a difference compared to most BHBs, the presence of a variable accretion disc, a corona, and jets make it a prototypical object to study the properties of accretion flows, and their connections with ejections of material. Spectral states were indeed first defined from the spectra observed in this source: Cyg X-1 can be found in both the so-called “low” hard state (LHS) or “high” soft state (HSS); between 2003 and 2010 it was predominantly in the LHS. between 2010 and 2014 (**TBC**) Cyg X-1 spent most of its time in the HSS (e.g. Grinberg et al. 2013). Partial (or “failed”) transitions from the LHS to the HSS, during which Cyg X-1 and can be found in a transitional or intermediate state (IS, e.g., Pottschmidt et al. 2003), are sometimes seen. Cyg X-1 belongs to the pair of Galactic microquasars where compact relativistic jets in the LHS have directly been imaged with VLBI technics (Stirling et al. 2001).

In Cyg X-1 the presence of a high energy spectral tail extending up to the MeV domain is known for almost 20 years (e.g. Grove et al. 1998). Its presence has recently been confirmed with the two main instruments onboard the ESA’s INTErnational Gamma-Ray Astrophysics Laboratory (*INTEGRAL*) by Cadolle Bel et al. (2006) and Laurent et al. (2011) with IBIS, and Jourdain et al. (2012) with SPI. In Laurent et al. (2011), we have shown that the $\geq 400\,\mathrm{keV}$ emission of Cyg X-1 was polarized at a level of about 70%, a result independently confirmed by Jourdain et al. (2012) using SPI data. Both studies, however, made use of the whole dataset available at the time of their publication regardless of the source spectral state.

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2 Separation of the data into spectral states

In order to improve the analysis and the understanding of the origin of hard X-ray tails it is important to separate the observations by spectral states. This way the spectral parameters and, hence, the properties of the emitting media, are not mixed and can be better interpreted. We used model-independent criterion based on all-sky monitors that is fully described and tested in Grinberg et al. (2013) to separate all the *INTEGRAL* (0.02–2 MeV) and AMI-Ryle (15 GHz) observations of Cyg X-1 obtained between 2003 and December 2012. The details of the data reduction are given in Rodriguez et al. (2015). Fig. 1 shows the Ryle-AMI (15 GHz) and *INTEGRAL*/IBIS (20–40 keV) long term light-curves with a color coding indicating the spectral state of the source as deduced with the above criteria (see Grinberg et al. 2013; Rodriguez et al. 2015, for all details of the method and the application to the current dataset).

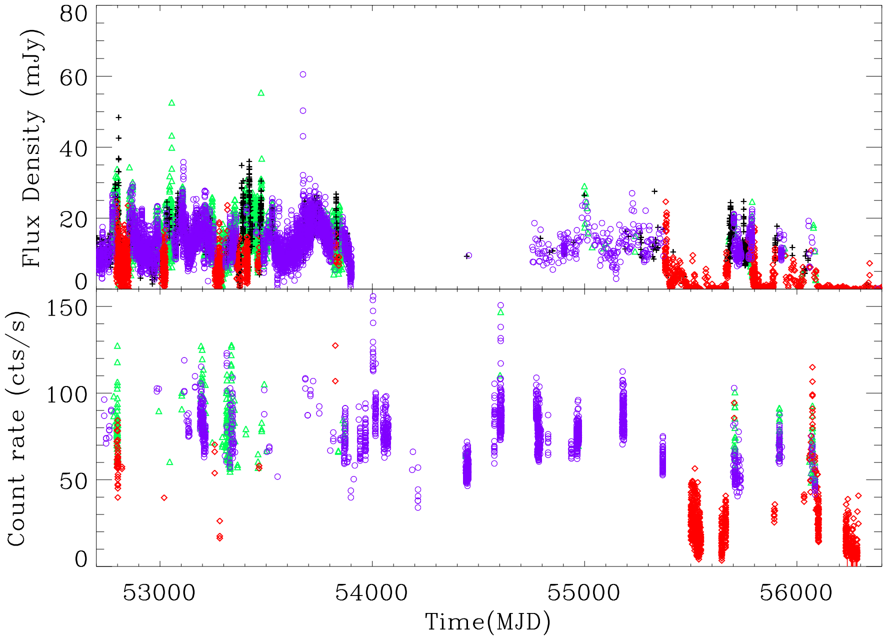

Fig. 1. Long-term 15 GHz Ryle-AMI (upper panel) and 20–40 keV *INTEGRAL*/IBIS (lower panel) light curves of Cyg X-1. The color coding indicates the spectral state of the source: purple is for the LHS, green for the IS, red for the HSS, and black shows observations where a classification was not possible.

3 State dependent analysis

3.1 *Radio behavior: a compact jet in the LHS*

Cyg X-1 is very variable in radio (Fig. 1). It shows quiescent periods, periods with relatively steady activity and flares. Our spectral classification shows that, as in other sources, the specific radio behavior is related to the spectral state: little or no radio emission is seen in the HSS, while the LHS is associated with a definite radio activity. Flares seem to occur in conjunction with or close to transitions from one state to another. Considering the entire data base we estimate the following mean state resolved radio fluxes: $\langle F_{15\,\mathrm{GHz,LHS}}\rangle = 13.5\,\mathrm{mJy}$, $\langle F_{15\,\mathrm{GHz,IS}}\rangle = 15.4\,\mathrm{mJy}$, and $\langle F_{15\,\mathrm{GHz,HSS}}\rangle \lesssim 9\,\mathrm{mJy}$. The level of radio detection and the relative steadiness of the source is compatible with the presence of a compact jet in the LHS as already seen in this source and others (e.g. Stirling et al. 2001; Corbel et al. 2003; Coriat et al. 2011).

3.2 *High energy spectral analysis: a hard tail in the LHS*

Fig. 2 shows the state-resolved 0.01–2 MeV *INTEGRAL* spectra. The 0.01–0.4 MeV spectra are all well represented by either a cut-off powerlaw or thermal Comptonization and a reflection component, even though the spectral shapes and fluxes are obviously different (see Rodriguez et al. 2015, for the details of the spectral modeling, and the spectral parameters obtained).

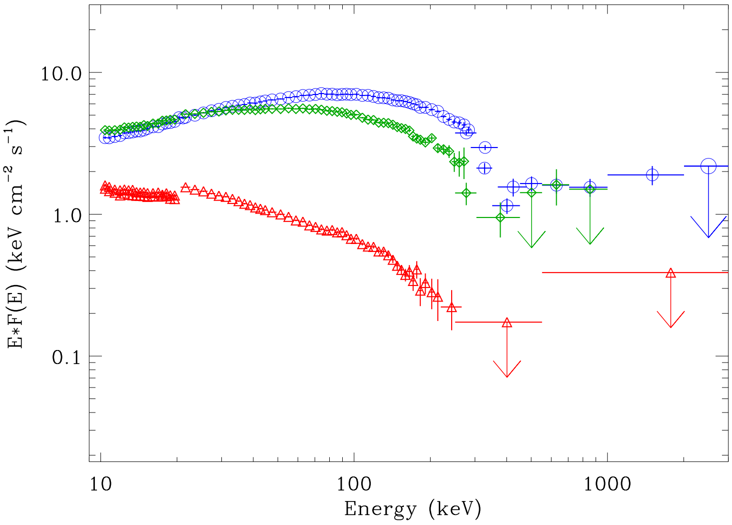

Fig. 2. *INTEGRAL* ”ν-Fν” spectra of Cyg X-1 in all three states. Blue is the LHS, green the IS, and red the HSS.

This model, however, fails at reproducing the 0.4–2 MeV LHS spectrum, and the inclusion of an additional $\Gamma = 1.4^{+0.2}_{-0.3}$ power law is needed in this state. The 0.4–1 MeV flux of this component is 1.9×10^{-9} erg cm^{-2} s^{-1}. It is not required in the other states with 3σupper limits of 1.5×10^{-9} erg cm^{-2} s^{-1}and 0.9×10^{-9} erg cm^{-2} s^{-1}in the IS and HSS respectively.

3.3 Polarimetric analysis: a 0.4–1 MeV polarized signal in the LHS

To study the properties of high energy polarization we took advantage of the two-layer nature of the IBIS detectors and consider only the events that interact in both the low and high energy detectors. In case of a polarized signal, Compton diffusion from the upper layer into the lower one preferentially follows a direction perpendicular to the polarization angle (e.g. Forot et al. 2007; Rodriguez et al. 2015, and references therein). By studying the distribution of detected counts with respect to the azimuthal angle (hereafter referred to as polarigrams) one can estimate the level of polarization (if any) and the polarization angle (PA). Fig. 3 shows the polarigrams obtained from the LHS data in two spectral domains, one corresponding to the energies where the source spectrum is dominated by the Comptonized component (below 450 keV) and one where the source spectrum is dominated by the hard tail (above 450 keV). While the lower energy polarigram is compatible with a flat line, the high energy one shows the definite presence of polarized emission. We estimate a polarization

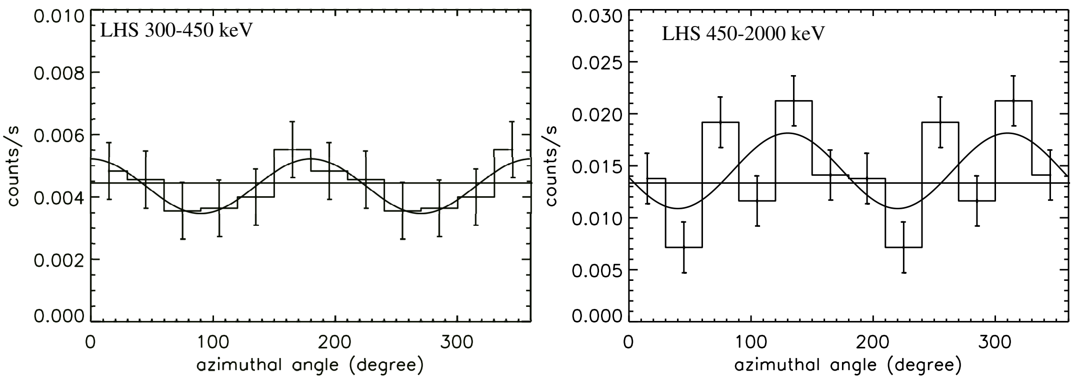

Fig. 3. LHS polarigrams. **Left:** 300–450 keV **Right:** 450–2000 keV.

fraction of 75±32% with a polarization angle PA=40° ± 14°. We do not detect any polarized signal in the HSS with an upper limit for the polarization fraction of 70% between 0.4–2 MeV. In the IS the short exposure time does not allow us to obtain a meaningful constraint.

4 Conclusions

Our state dependent analysis shows :

- The 0.01–400 keV spectra of Cyg X-1 are well represented by either a cut-off power law or (thermal) Comptonization and a reflection component, with parameters that are clearly distinct from one state to another.
- The presence of a hard tail dominating the 0.4–1 MeV emission in the LHS.
- The hard tail is below the detection sensitivity in the other states and we obtain a 3σ upper limit on the hard tail flux in the HSS that is half the flux emitted in the LHS.
- We detect a clear polarized signal in the 0.4–2 MeV LHS data only. In the other states we estimate an upper limit for the polarized fraction of 70% between 0.4–2 MeV in the HSS, and we do not obtain meaningful constraint in the IS.
- Radio emission is clearly detected in the LHS and in the IS. The level of radio in the HSS is compatible with no or little emission.

The large polarization value implies synchrotron radiation and a very ordered magnetic field. A jet is a natural medium for synchrotron emission, and all models of jets rely on the presence of an ordered magnetic field, and predict synchrotron emission. Our observations do show the presence of a jet in the state where the polarized tail is found. We therefore favor a jet origin for the hard tail polarized component. We note that a coronal origin has recently been suggested as the origin of the polarized signal (Romero et al. 2014). This however relies on an underlying synchrotron emitting medium (taken to be the corona) which undergoes Compton scattering in the corona. While this suggestion opens interesting possibilities, it would need the corona to be highly structured (in its innermost regions) in order to produce the polarized (synchrotron) signal. The coronal optical depth/density also needs to be rather low, to not exceed the low number of Compton scatterings necessary to maintain the high level of polarization. While the cannot completely exclude such a geometry, we think that it needs too much fine tuning, and we clearly favor the interpretation which we think is better supported by observational facts, namely the presence of a jet.

5 Literature citations

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