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Characteristic geometries of accretion in Cyg X-1 found with INTEGRAL

P. Lubiński[1], A. Filothodoros[1], A.A. Zdziarski[2], and G. Pooley[3]

[1] Institute of Physics, University of Zielona Góra, Licealna 9, PL-65-417 Zielona Góra, Poland, e-mail: P.Lubinski@if.uz.zgora.pl
[2] Centrum Astronomiczne im. M. Kopernika, Bartycka 18, PL-00-716 Warszawa, Poland
[3] Cavendish Laboratory, J. J. Thomson Avenue, Cambridge CB3 0HE, United Kingdom

Abstract. Thanks to observations of the black hole binary Cyg X-1 carried over 15 years the INTEGRAL satellite collected the largest data set in the hard X-ray band for this source, exceeding 18 Ms of exposure time. We analysed these data, complemented by the radio flux measured by AMI Large Array. To characterize the spectral and variability properties of the system we determined parameters such as the hard X-ray flux, photon index and fractional variability. We found that the distribution of the photon index determined for the 22–100 keV band can be decomposed into four Gaussian peaks. This result, interpreted within the Comptonization scenario as a dominant process responsible for the hard X-ray emission, leads to a conclusion that the hot plasma region in Cyg X-1 takes form of four specific geometries. A distinct character of each of these states is strengthened by different X-ray and radio variability patterns. In particular, the hardest state shows no flux - photon index correlation typical for the three other states, what can be interpreted as a lack of interaction between the plasma and accretion disk.

Key words. Stars: black holes – X-rays: binaries – X-rays: individuals: Cygnus X-1

1. Introduction

Dominant radiation from the black hole binary (BHB) systems is observed in the X-ray band. Variability of this emission is the basis of classification of the BHB spectral states (Belloni & Motta 2016). The two main states are the soft state associated with the prevailing emission from the accretion disc and the hard state when the hot plasma emission is stronger. Besides, there are several other states observed, usually having transitional properties between the two main states (Belloni 2010). Varying radiation from the disc and plasma region are accompanied by a changing level of radio-to-UV emission from the outflowing matter, in a form of jets and winds (Fender & Muñoz-Darias 2016).

Spectral state classification is typically based on the soft X-ray emission (< 20 keV) due to the number of photons emitted in this band being much larger than that observed in the hard X-rays. Parameters used to select the state are either the numbers of counts registered in two or more energy bands and their ratio (hardness ratio, e.g. Grinberg et al. 2013) or photon indexes derived for different energy bands (e.g. Zdziarski et al. 2002). A caveat of the classification using the data below 20 keV is that the emission of many objects in that band is complex and affected by a variable absorption. On the other hand, the data above 20 keV are dominated by the plasma emission, enabling an unambiguous investigation of the plasma properties. A huge amount of data in the 22–100 keV band, collected by the ISGRI detector of the *INTEGRAL* satellite for Cyg X-1 binary, motivated us to check whether getting a deeper insight into the system geometry is possible.

2. Data analysis

Our main data set was the *INTEGRAL*/ISGRI information on the 22–100 keV emission from Cyg X-1 collected over 2002–2017 period (satellite orbits 0022– 1882). In total, we have selected 7821 so-called science windows (an interrupted observation lasting typically 0.5–2.0 hours), filtering out observations affected by a high background. The total exposure time of these 7821 science windows is 18.5 Ms. In addition, we have used the softer X-rays data (3–12 keV) from the JEM X-1 detector of *INTEGRAL* and the radio data at 15 GHz collected by the AMI array (Zwart et al. 2008). Since the ISGRI calibration evolved over the *INTEGRAL* mission period, we have used the flux $F_{\rm H}$ and the photon index $\Gamma_{\rm H}$ determined through the fit of the power-law model to the 22–100 keV spectra, to correct the data with the response files taking into account the detector evolution. Besides this two simple parameters characterizing the spectral shapes we extracted the fractional variability amplitude $S_{\rm V}$ (Almaini et al. 2000) for each science window, with a 1 minute time bin.

3. Results

The distribution of the 22–100 keV flux and photon index for all science windows is shown in Fig. 1. In our $\Gamma_{\rm H} - F_{\rm H}$ plot there are apparent several regions: two clusters corresponding to the hard state ($\Gamma_{\rm H} < 1.92$), slightly larger cluster of the intermediate state, and extended soft state region with fluxes typically below $70{\times}10^{-10}$ erg cm^{-2} s^{-1}.

Distribution of the photon index $\Gamma_{\rm H}$ is shown in Fig. 2, together with its deconvolution into four substates approximated with the Gaussian model. The fitted positions of the

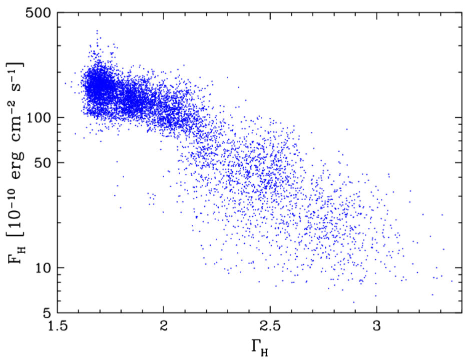

Fig. 1. Hard X-ray flux $F_{\rm H}$ plotted against the hard X-ray photon index $\Gamma_{\rm H}$.

four peaks are 1.70, 1.83, 2.03, and 2.56, with a fraction relative to the entire distribution equal to 29%, 25%, 19%, and 27%, respectively.

To explore the hour-scale variability of the hard X-ray spectra we have computed the Spearman rank order coefficient $r_{\rm S}$ for the $\Gamma_{\rm H} - F_{\rm H}$ correlation using each *INTEGRAL* orbit with at least 10 science windows. Our analysis was also extended to the softer X-ray band, for which we have extracted the 5–12/3–5 keV hardness ratio $H_{\rm S}$ from the JEM X-1 observations, being exactly contemporary to the ISGRI observations. In Figs. 3 and 4 we present the values of the soft hardness ratio $H_{\rm S}$, hard X-ray variability amplitude $S_{\rm V}$, 15 GHz AMI radio flux $F_{\rm R}$ and the Spearman coefficient $r_{\rm S}$ plotted in against the hard X-ray flux $F_{\rm H}$ and photon index $\Gamma_{\rm H}$, respectively.

The hard X-ray flux is clearly correlated with the first three parameters, shown in panels (a,b,c) of Fig. 3. In particular, the amplitude of the hard X-ray variability is much stronger during the soft state. This is different from the typical trend observed for soft X-ray, where the hard state appears to be more variable (Belloni & Motta 2016). In the case of radio emission our results confirm previous findings of the highest fluxes observed for bright but not the brightest hard X-ray emission (Wilms et al. 2006; Zdziarski et al. 2011).

All correlations between the four parameters and the photon index $\Gamma_{\rm H}$ presented in Fig. 4 are more evident than that shown in Fig. 3.

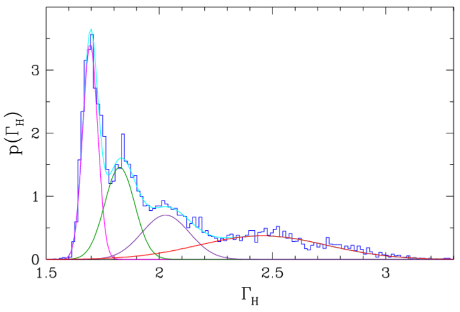

Fig. 2. Deconvolution of the Γ_H distribution into four Gaussians corresponding to the pure hard, transitional hard, intermediate and soft state, starting from the left.

We observe a distinct stratification of the data in each region (substate) of Γ_H. The lowest hard X-ray variability is seen for the softer hard state, whereas the highest radio flux is reached during the intermediate state. The most striking is the lack of the $\Gamma_H - F_H$ correlation during the hardest state, with r_S being quite symmetrically distributed around 0.

4. Discussion

Our main finding is that the hard X-ray photon index exhibits a clear clustering, especially for the hard state where the two sharp peaks in the Γ_H distribution are observed. Correlation between the spectral slope and flux is usually interpreted as the result of interaction between the hot plasma and the soft photons coming from the accretion disc, with the varying inner radius of the disc (Esin et al. 1997). Since this correlation disappears in the hardest state, we called this state the pure hard state. We never observe a direct transition from this state to the intermediate or soft state, with the second, softer hard state being always a midway state, called the transitional hard state.

An existence of the pure hard state can be explained by the synchrotron boiler model with only the plasma soft photons Comptonized by the hot electron population (Malzac & Belmont 2009). This model predicts the photon index around 1.7 for various combinations of the other model parameters. Therefore, the pure hard state observed for Cyg X-1 can be interpreted as a limiting geometry of the system, with the plasma region concentrated close to the black hole horizon and almost not interacting with the accretion disc, possibly truncated at large radius. Interestingly, similar values of the photon index grouped around 1.7 were found for the average spectra of a sample of radio-quiet Seyfert galaxies Lubiński et al. (2016). This fact, and also similar ranges of the plasma temperatures extracted for these objects and Cyg X-1 suggest a common limiting geometry of the accreting systems characterized by a large range of the black hole mass.

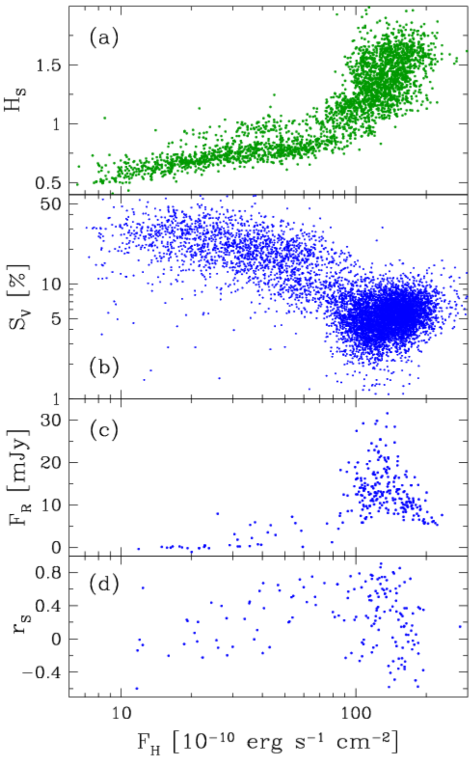

Fig. 3. The soft X-ray hardness ratio H_S, hard X-ray variability amplitude S_V, radio flux F_R and the Spearman coefficient r_S plotted against the hard X-ray flux F_H.

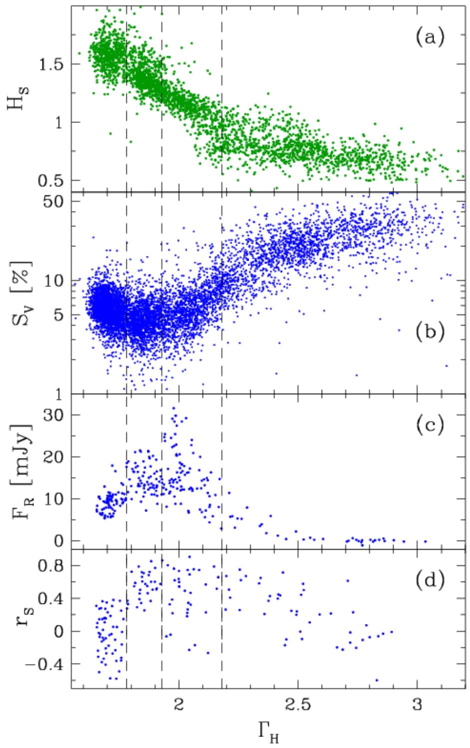

Fig. 4. The soft X-ray hardness ratio H_S, hard X-ray variability amplitude S_V, radio flux F_R and the Spearman coefficient r_S plotted against the hard X-ray photon index Γ_H. Dashed lines show approximate borders of the four states found through a deconvoluion of the Γ_H distribution.

5. Conclusions

Analyzing a large data set from the *INTEGRAL* observations of Cyg X-1 we found that the distribution of the hard X-ray photon index shows four peaks, where the hard state is separated into two substates: pure and transitional. The pure hard state can be explained with the synchrotron self-Compton model with the seed soft photons coming exclusively from the plasma itself. All four states show different properties, in particular a different variability amplitude and different ranges of the radio emission. This differences point towards four specific geometries of the system, associated with a changing jet emission.

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