Abstract

Thanks to recurrent observations of the black hole binary Cyg X-1 carried out over 15 years the INTEGRAL satellite has collected the largest data set in the hard X-ray band for this source. We have analyzed these data, complemented by data collected by other X-ray satellites and radio flux at 15 GHz. To characterize the spectral and variability properties of the system we have examined parameters such as the hard X-ray flux, photon index, and fractional variability. Our main result is that the 2D distribution of the photon index and flux determined for the 22–100 keV band forms six clusters. This result, interpreted within the Comptonization scenario as the dominant process responsible for the hard X-ray emission, leads to a conclusion that the hot plasma in Cyg X-1 takes the form of six specific geometries. The distinct character of each of these plasma states is reinforced by their different X-ray and radio variability patterns. In particular, the hardest and softest plasma states show no short-term flux–photon index correlation typical for the four other states, implying a lack of interaction between the plasma and accretion disk. The system evolves between these two extreme states, with the spectral slope regulated by a variable cooling of the plasma by the disk photons.

1. Introduction

Binary systems hosting a black hole (BH) can be subdivided into persistent and much more numerous transient sources (e.g., Tetarenko et al. 2016). Both classes are observed in several X-ray spectral states, followed by distinct properties of the emission from radio to UV bands (e.g., Belloni & Motta 2016). The three basic states are the soft (or high) state (SS) with a stronger soft X-ray emission, the hard (or low) state (HS) when the hard X-ray emission dominates, and the intermediate state (IS) corresponding to a transition between the two other states. There is a consensus that these states are associated with various arrangements of the accretion disk, plasma region(s), and outflowing material, the last in the form of jets or winds (e.g., Fender & Muñoz-Darias 2016). However, there are many different propositions of the actual scenario of the system’s geometry evolution. Prevailing are those invoking a varying inner radius of the disk as a main driver of the system changes (e.g., Esin et al. 1997), i.e., related to the advection-dominated accretion flow models (Narayan & Yi 1994; Abramowicz et al. 1995) with a hot inner flow replacing the disk. Alternative to the truncated disk scenario are, for example, models with a magnetized disk of constant size where the state transitions result from varying strength of the toroidal component of the disk field ( Begelman et al. 2015).

Studies of spectral states of BH binaries (BHBs) were intensified in the mid-1990s when the Rossi X-ray Timing Explorer (RXTE, Bradt et al. 1993) started operation. Besides a detailed modeling of the high-quality spectra, several phenomenological tools were developed: the hardness–intensity diagrams (HIDs), the fractional rms variability (rms)–intensity diagrams, and the hardness–rms diagrams (HRDs). Whereas transient BHBs typically follow the so-called q-shaped track in HIDs, persistent BHBs show rather only a fraction of that track (Belloni & Motta 2016).

Varying energy spectra and variability explored through the rms, power-density spectra (PDS), coherence, and lags studies resulted in an extension of the state classification. Many transient sources exhibit a phase of very strong disk emission coupled with a prominent steep power-law continuum at higher energies, the so-called very high state (VHS) or steep power-law state (e.g., McClintock & Remillard 2006). Transitions between the SS and HS states were found to show two different phases, introducing the soft intermediate state (SIMS) and hard intermediate state (HIMS) instead of a single IS for transient systems (e.g., Belloni 2010).

An unambiguous, though simple, method of state classification is vital to get deeper insights on the physics of accreting BHBs. The most reliable selection is usually obtained with criteria based on color–color or slope-slope diagrams, whenever the X-ray spectra are available (e.g., Zdzierski et al. 2002; Wilms et al. 2006; Gierliński et al. 2010). Nevertheless, to fully explore the evolution of both transient and persistent systems, the X-ray-monitoring data and HRD-based selection must be applied, at the expense of a somewhat weaker identification of the IS (Grinberg et al. 2013).

Cyg X-1, the first BHB detected (Bowyer et al. 1965) and one of the brightest, persistent hard X-ray sources, hosts a BH and a blue supergiant, HD 226868. Thanks to the brightness of Cyg X-1, a wealth of information about its nature has been gathered. However, being one of only several known high-mass, wind-fed persistent BHBs, it might be not quite representative of the BHB class in general. Indeed, the HID diagram for Cyg X-1 does not show a typical q-track, occupying only a part of the region covered typically by the transient systems (Belloni 2010). This can be related to a relatively small range of the bolometric luminosity observed for this source, varying by a factor ≲10 (Wilms et al. 2006; Zdziarski et al. 2011). The transitions between the SS and HS state occur at the same flux level in both directions, whereas the transient systems display a hysteresis behavior. Moreover, during the SS Cyg X-1 does not reach very low level of rms variability, typical of that state in other systems (Belloni 2010).
Variability studies at soft X-rays revealed that the HS in which Cyg X-1 is observed for most of the time changed for a quite long period into a slightly softer HS, showing a number of failed transitions into the SS (Pottschmidt et al. 2003b). Cyg X-1 belongs to the anomalous track class, exhibiting a stronger radio-soft X-ray correlation than that typically observed for transient BHBs (Zdziarski et al. 2011). In the hard X-ray band this correlation becomes more complex, with the highest radio emission observed for medium X-ray fluxes (Wilms et al. 2006; Zdziarski et al. 2011).

The vast majority of extensive studies of Cyg X-1 spectral states were based on RXTE data, predominantly limited to the 3–35 keV band. Emission in this band is commonly thought to be a mixture of the primary emission of the disk and hot plasma, accompanied by Compton reflection of the plasma radiation from the disk. Therefore, an interpretation of the results in terms of a complex physical model is usually demanding. On the other hand, the emission in the 22–100 keV band is dominated by the Comptonized continuum (see Figure 2 of Filothodoros et al. 2018), allowing for a more direct analysis of the plasma properties. There have been many spectral studies of the hard X-ray band exploring high-quality data from pointed observations (e.g., Gierliński et al. 1997; Del Santo et al. 2013) and various examples of a comprehensive analysis of a large data set covering a long period (e.g., Gleissner et al. 2004; Zdziarski et al. 2011).

INTEGRAL satellite (Winkler et al. 2003) observations provided a variety of valuable information on the nature of Cyg X-1 (e.g., Pottschmidt et al. 2003a; Zdziarski et al. 2012; Del Santo et al. 2013). INTEGRAL’s uninterrupted observation (science window) typically lasts 0.5–2 hr and the sensitivity of the ISGRI detector (Lebrun et al. 2003) allows one to obtain, within this period, data of a quality surpassing the daily averaged data from the hard X-ray monitors. This motivated us to perform an extensive analysis of the spectral states of Cyg X-1, based on the hard X-ray emission. A detailed analysis of the state-wise summed spectra with advanced Comptonization models must be postponed until the improved ISGRI calibration (OSA 11; see Section 2.1) is extended to the entire mission period.

2. Data Selection and Reduction

2.1. Integral

Our analysis utilizes all public INTEGRAL data released before 2018 March 1. These data were collected during the spacecraft orbits (revolutions), ranging from 22 up to 1882, i.e., within a period between 2002 December 18 08:55:11 UTC and 2017 November 8 03:04:31 UTC. INTEGRAL data were reduced with the OSA software package (Courvoisier et al. 2003), version 10.2 (ISGRI and SPI detectors) and version 11.0 (JEM-X 1 detector).

To investigate the hard X-ray properties of the spectral states of Cyg X-1 we used a large data set collected by the ISGRI detector in the 22–100 keV band. A main tool to study the spectral states is the HID. However, the hardness ratios depend strongly on the choice of the two energy bands. On the other hand, there are substantial changes in the ISGRI characteristics observed over the 15 years considered (Natalucci & Savchenko 2017). For this reason, we decided to use the photon index of a power-law model fitted to the 22–100 keV spectra instead of the hardness ratio. We have also computed the flux in the same band based on the fitted model. In this way, by applying a set of time-dependent instrument responses we have reduced the influence of the evolution of the ISGRI detector on both our basic parameters, characterizing the intensity and spectral slope.

The ancillary calibration files (ARFs) of OSA 10.2 for ISGRI were released in 2015 December and are not appropriate for data collected more than several months afterwards. To enable using data collected during the last two years of the analyzed period, we prepared our own spectral calibration. A set of five ARFs was generated by inverting the Crab spectra collected during 2016 and 2017, to ensure an overall agreement with the INTEGRAL’s standard model of the Crab spectrum, based on the SPI detector results (Jourdain et al. 2008). Although this approach can be insufficient for a detailed spectral analysis with complex models, it ensures a good correction of the fluxes measured in a relatively wide energy band.

The new OSA package, version 11, was released on 2018 October 19, and is valid only for the Cyg X-1 observations between revolutions 1626 and 1882. Using Crab observations from revolutions 1662–1887 we compared spectral fits obtained for OSA 10.2 with our ARFs and with OSA 11. Typically the Crab photon index in the 30–100 keV band from OSA 11 is less by 0.02–0.03 than that fitted to the OSA 10.2 spectra. This difference is a result of the new Crab spectral model adopted for OSA 11, with the reference photon index of 2.1 instead of 2.08 used before (Jourdain et al. 2008). We observe a similar effect of an overall spectral softening for Cyg X-1 data taken during the OSA 11 validity period. To avoid mixing various calibration versions for this project we used only OSA 10.2 with our ARFs for the recent observations.

The selection of the ISGRI data was based on a criterion of at least 10% of the detector area being illuminated by Cyg X-1, which corresponds roughly to observations with an off-axis angle <15°. This resulted in 8128 science windows filtered with the OSA software. For further analysis we selected 7907 science windows with a relative uncertainty of the count rate in the 22–100 keV band <10%. For each of them we extracted a six-channel spectrum (with energy limits: 22.1–25.0, 30.2–40.3, 52.7–70.4, 100.1 keV), analyzed later with the XSPEC fitting code, version 12.9.0n. The spectra were fitted with a power-law model, convolved with the cflux model to compute the flux and its uncertainty. The results are the hard X-ray photon index $\Gamma_{\text{H}}$ and the flux $F_{\text{H}}$ integrated in the 22–100 keV band. After this step, in order to reduce the uncertainty of the points in the $\Gamma_{\text{H}}$–$F_{\text{H}}$ diagram, we excluded all results with a relative $\Gamma_{\text{H}}$ error > 10%, obtaining 7844 science windows. Finally, we also excluded 23 science windows collected during revolutions 1554–1557 when the count rate of the outbursting V404 Cygni in the 22–40 keV band was higher than 1000 cps. After applying all the selection criteria the final data set consisted of 7821 science windows, with a total exposure time of 18.53 Ms (covering 3.9% of the entire studied period) and about 2.1 billion photons emitted by Cyg X-1 in the 22–100 keV band. The neglected low-quality data correspond mostly to the SS, decreasing its population by about 20%. As we have tested, an exclusion of those 307 science windows does not introduce any bias is our results.

Despite their relatively low sensitivity, the JEM-X detectors ensure exactly contemporary observations to the ISGRI.

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4 L. Natalucci, private communication.
The JEM-X field of view is smaller than that of IBIS and we used only data from observations when the source off-axis angle was below 5°. Tests done with the Crab data revealed a small discrepancy between the hardness ratios of both JEM-X detectors. To avoid artifacts when mixing the JEM-X 1 and JEM-X 2 results we decided to use only JEM-X 1 data. We used the standard OSA 11.0 software settings except for JEM-X 1 and JEM-X 2 results we decided to use only JEM-X 1 detector. The light curves of JEM-X 1 both JEM-X detectors. To avoid artifacts when mixing the revealed a small discrepancy between the hardness ratios of 2992 good science windows. The light curves of JEM-X 1 detector were extracted in two energy bands: 3–5 keV and 5–12 keV.

In the case of the SPI detector we used the spiros software included in OSA 10.2, set to the SPECTRA mode. Each spectrum was extracted with six linear energy channels in the 22–100 keV band. The background was estimated using the GEDSAT background model. The other options of the spiro_analysis routine were set to their default values and all known bad pointings were automatically ignored. In total, 7772 single science window spectra were fitted with a power-law model. The sensitivity of SPI below 100 keV is lower than that of ISGRI and for this reason we had to exclude a much larger fraction of data. After a selection based on the photon index uncertainty \( \leq 0.1 \), 2894 science windows were used for further analysis.

2.2. Other Observatories

Since the spectral state classification of Cyg X-1 is usually based on analysis of the X-ray data below \( \approx 20 \) keV, INTEGRAL’s data have to be complemented by data taken by other X-ray observatories. In addition, to deepen our analysis we used radio data from a contemporary monitoring of Cyg X-1.

The All-Sky Monitor (ASM; Levine et al. 1996) on board the RXTE satellite monitored Cyg X-1 in the 1.5–12 keV band. We used the data in the three ASM sub-bands, 1.5–3 keV, 3–5 keV, and 5–12 keV, taken from the ASM Archive covering the period contemporaneous to INTEGRAL’s observations, MJD 52262–52200 (the ASM data taken after MJD 55200 were ignored; see Grinberg et al. 2013). Depending on our purposes, we used either the orbital or daily averaged data.

After the RXTE mission completion the main instrument used for the soft X-ray monitoring is the Monitor of All-sky X-ray Image (MAXI; Matsuoka et al. 2009) on board the International Space Station. MAXI provides data in three energy bands: 2–4 keV, 4–10 keV, and 10–20 keV. We used both the orbital and daily averaged data, downloaded from the mission archive. The daily averaged spectra of MAXI’s Gas Slit Camera (GSC) were extracted with the mxproduct tool included in the HEASOFT package (Matsuoka et al. 2009).

BATSE data were downloaded from the Earth Occultation Data Products archive. The daily spectra were extracted following the Earth occultation analysis described in Harmon et al. (2004). We used the HEASOFT bod2pha tool, setting the minimum number of flux determinations to four for each module of the large-area detector (LAD). The spectral response for each viewing period and each LAD module was generated with the HEASOFT bod2rmt tool. In total, we got 2728 daily spectra for a period between 1991 May 2 and 1999 September 15. The spectra of each LAD module were fitted together in the 22–100 keV band with a power-law model. The photon index for a given day was computed as a weighted mean of photon indices fitted to all individual module spectra.

The Burst Alert Telescope (BAT) detector (Krimm et al. 2013) on board the Neil Gehrels Swift satellite (Gehrels et al. 2004) operates in an energy band similar to INTEGRAL’s ISGRI, namely 14–195 keV. Its sensitivity is slightly lower than that of ISGRI and its mean exposure time for a single day monitoring of Cyg X-1 is 91 ± 70 min, i.e., of the order of typical duration of a single INTEGRAL science window. We used BAT’s continuous monitoring data in the 15–50 keV band.

The largest radio data set of the Cyg X-1 monitoring contemporary to the INTEGRAL mission is that collected by the Ryle Telescope (RT; Jones 1991, before MJD 53903) and its successor, the Arcminute Microkelvin Imager (AMI; Zwart et al. 2008, after MJD 54752). The RT bandwidth is 0.35 GHz at 15 GHz, whereas AMI covers a frequency range between 13.5 and 18 GHz, also centered at 15 GHz. A typical exposure time was \( \approx 10 \) minutes and Cyg X-1 was observed \( \approx 10 \) times per day. The RT and AMI data that we use here were already published by Zdziarski et al. (2017, 2020).

3. Results

3.1. Long-term Variability of Cyg X-1

In Figure 1 we present several parameters derived from the data collected by the ISGRI, ASM, MAXI, and BAT detectors together with the radio flux measured by the RT and AMI for a period of the Cyg X-1 monitoring analyzed by us (MJD from 52262 to 58065). All data were rebinned to a 1 day time bin. The points are colored according to the state selection of Grinberg et al. (2013, see their Table 2). Using joint ASM +MAXI data we computed that the source spent 64%, 10%, and 26% of the time in the HS, IS, and SS, respectively.

In panels (a) and (b) of Figure 1 the ASM (5–12/1.5–3) keV hardness and the MAXI (4–10/2–4) keV hardness are shown, respectively, both being good tracers of the state system. The other panels of Figure 1 present the Swift/BAT flux in the 15–50 keV band (c), the ISGRI 22–100 keV flux \( F_H \) (d), photon index \( \Gamma_H \) (e), and the RT/AMI 15 GHz flux (f). As shown in Figure 7 of Grinberg et al. (2013), the IS region defined for MAXI is relatively narrow and this is seen also in our results, with a quite narrow band of intermediate data in Figure 1(b). For this reason there are several periods after MJD 55400 during which the SS selected with MAXI corresponds to a hard X-ray (BAT) and radio emission observed at levels typically seen during the IS or HS. Taking into account energy bands other than the soft X-ray band, Figure 1 demonstrates that the hard X-ray photon index is a very good indicator of the HS, whereas the radio and hard X-ray fluxes are valuable for the SS selection.

3.2. Plasma States in Cyg X-1

Figure 2 presents the ISGRI 22–100 keV flux \( F_H \) as a function of the best-fit photon index \( \Gamma_H \) of the power-law model fitted in the same band to the single science window spectra. We use this plot as a hard X-ray counterpart of an HID used to

5 http://xte.mit.edu/asmlc/ASM.html
6 http://maxi.riken.jp/sugizaki/s51/
7 https://heasarc.gsfc.nasa.gov/docs/cgiro/batse/
8 https://swift.gsfc.nasa.gov/results/transients
study spectral evolution of various binary systems in the soft X-ray band. In general, data shown in Figure 2 form two distinct regions, a relatively well concentrated high-flux region corresponding to the HS and a major part of the IS, and a much more dispersed region corresponding to the SS.

To better visualize the data clustering and reveal some features of the $\Gamma_H$–$F_H$ distribution we have computed its 2D density map, presented in Figure 3. The density of data points was computed for pixels separated by $\Delta \Gamma_H = 0.005$ and $\Delta \log(F_H) = 0.007$, over an ellipse with the $\Gamma_H$ and $F_H$ semi-axes 10 times larger than the pixel separation. We tried several options of the pixel distances and integration region sizes, choosing the one best showing both local density peaks and the regions edges or valleys between them. Also the color coding was adjusted to reveal those features with rather contrasted instead of smoothly transiting shades.

The density map shown in Figure 3 reveals two main regions, the hard and soft regimes, well separated by the flux level of $75 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$. In both regimes we observe three subregions, forming two sharp peaks for $\Gamma_H < 1.93$, two flatter ridges in the soft–hard transition region ($1.93 < \Gamma_H < 2.29$), and two dispersed peaks for the soft data ($\Gamma_H > 2.29$). From now we call these regions: pure hard (PH), transitional hard (TH), hard intermediate (HI), soft intermediate (SI), transitional soft (TS), and pure soft (PS) states, with the exact $\Gamma_H$ and $F_H$ limits provided in Table 1. This nomenclature and
adopted limits will be explained in Sections 3.3 and 3.4, where various properties of these states are discussed.

Since this is the first time such a clustering of parameters describing the plasma in the accreting BH system has been presented, we have to examine its reliability. There is a variety of simple heuristic clustering tests, but most of them lack the means to assess the relative probability between the hypotheses of different numbers of clusters. This limitation can be solved using methods based on probability density models with the Bayes information criterion applied to discriminate between them (Fraley & Raftery 2002). In case of our data a construction of such density models can be demanding due to the (possibly) non-Gaussian shape of the regions. However, for such high-density gradients and quite regular shapes as observed in Figure 3, those methods should confirm the presence of at least five clusters (except for the HI state). To prove this we have made a simple estimate of the probability that the low-density valley seen between the two SS regions appears by chance.

The solid line in Figure 3 connects the centers of these two SS regions. The valley is more or less perpendicular to this gradient line. We have computed the numbers of data falling into rectangular regions with centers located along this line. Two examples of such regions are shown in Figure 3. We have tested several sizes of these rectangles. An example of the results of this density gradient study is presented in Appendix A. As a null hypothesis (a single SS) we applied several options of a pure or deformed Gaussian density distribution. If these models describe data, there are about 60 points missing in the valley (see Figure A1). These points must be shifted by a statistical fluctuation to the one of the peak regions. As shown in Figure 2, the typical 1σ uncertainty of $\Gamma_H$ in this region of the diagram is about 0.1, i.e., slightly smaller than the expected shift. Thus an upper limit for a probability that a single point is shifted from the valley to one of the peaks corresponds to 1σ probability, 0.32. Hence the joint probability of such coherent fluctuation of the position of 60 points in the diagram will be smaller than (0.32)$^{60} \approx 2 \times 10^{-30}$.

For the other pairs of neighboring regions seen in Figure 3 the density gradients between them are similar or stronger in terms of the number of points that must be shifted (note the log-scale of the density). In addition, they have to be shifted by more than several $\sigma$ (see errorbars in Figure 2), thus their separation must be statistically highly probable. The only exception is the HI state region appearing as an extension of the HS region (but see the Figure 3 insert showing a better separation). In Sections 3.3 and 3.4 we demonstrate that this region exhibits several properties distinct from those of the two HSs.

Besides purely statistical fluctuations we considered an issue of our simplistic spectral model in a form of the power law. Neglecting the continuum curvature due to Compton reflection, high-energy cut-off, and other effects can lead to an artificial photon index clustering. In Filthodoros et al. (2018) almost the same INTEGRAL data set was analyzed through spectral fitting of a hybrid Comptonization model, eqpair. Using their results we performed a test to check if the power-law model fitted to the spectra simulated with a realistic shape changing smoothly with spectral hardness can induce a spurious aggregation of the $\Gamma_H$ values. The test details and results are presented in Appendix B. The simulations demonstrated that the $\Gamma_H$ distribution is modified by varying all main parameters of the eqpair model, not only those controlling the reflection and high-energy cut-off. Nevertheless, our test demonstrated that an approximation of the spectral shape with the power-law model does not introduce any specific $\Gamma_H$ aggregation. Thus, our clustering results turn out to be essentially free from both statistical and systematic effects. In the rest of this section and Sections 3.3 and 3.4 we consider several other parameters characterizing the Cyg X-1 emission, showing that they expose in various ways the distinct nature of the six states found with the $\Gamma_H$-$F_H$ density diagram. Figures 4 and 5 present these parameters as a function of $\Gamma_H$ and $F_H$, respectively. The corresponding Tables 1 and 2 summarize the results of statistical analysis of various properties of the six states, in terms of the mean values and correlations, respectively.

Although the density data in Figure 3 for the hard and soft regimes depend on both $\Gamma_H$ and $F_H$, the hard photon index is the primary parameter that enables the separation of the six states. In panel (e) of Figure 4 we show the $\Gamma_H$ distribution and its decomposition into six Gaussians, providing quite a good approximation (reduced $\chi^2$ around 1.2). This fit should be treated with caution because the peaks shown in Figure 3 are not quite symmetric and there is an overlap between both ISs. Therefore, we use the fitted curve only to guide the eye (see Section 3.6).

The first quantity confronted with $\Gamma_H$ and $F_H$ is the JEM-X X-1 hardness ratio $H_X$ (panel (a) of Figures 4 and 5). The JEM-X data should be corrected for orbital modulated absorption, which can reach quite high values (Grinberg et al. 2015). However, such a correction is not possible without a detailed spectral analysis, out of the scope of this paper. When the JEM-X X-1 3–12 keV count rate data are plotted against the orbital phase (according to Gies et al. 2008), we do not see a clear general trend, either for the entire data set or state-wise selection. Therefore, we use uncorrected data, which introduces some scatter in the results.

As shown in Table 2, the hardness ratio $H_X$ does not correlate with $\Gamma_H$ for the PH and SI states, strongly anticorrelates for the TH, HI, and TS states, and shows weak anticorrelation for the PS state. Correlations between $F_H$ and $H_X$ are positive and

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*All single-parameter distributions shown in this paper are computed as the probability density functions, i.e., taking into account the abscissa units and normalized to give the total integral equal to 1.*
strong for the four softer states, very weak for TH state, and weak for PH state. An important issue seen in Figure 4(a) is that the soft X-ray hardness cannot be used to identify the six plasma states found by us due to a lack of a clear segregation of the $H_S$ values. In particular, the PH and TH states cannot be separated and the three softest states are strongly mixed. The two IS data points between $G_H = 1.93$ and 2.29 occupy different ranges of the $H_S$ range, as shown in red in Figure 4(a); however, this does not allow for a good separation.

### 3.3. Hard X-Ray Variability

#### 3.3.1. Fractional Variability

The second fundamental diagram, besides the HID, commonly applied to characterize the behavior of BHBs, is the HRD (e.g., Belloni 2010). To construct a similar diagram with the ISGRI data, we have computed a normalized fractional variability amplitude $S_V$ expressed as

$$ S_V = \left( \frac{\sigma_V}{\bar{\sigma}} \right) \times 100\%, $$

with the fractional variability amplitude $\sigma_V$ fulfilling an equation derived by Almaini et al. (2000)

$$ \sum_{i=1}^{N} \frac{(c_i - \bar{\sigma})^2 - (\sigma_i^2 + \sigma_V^2)}{\sigma_i^2 + \sigma_V^2} = 0, $$

where $c_i$ is the count rate measured for a given time bin, $\sigma_i$ is its statistical error, $\bar{\sigma}$ is the mean count rate for a given science window, and $N$ is the number of time bins within the science window period.

The time bin adopted for this analysis was 1 min. With this, a relative statistical uncertainty of the count rate for a single measurement was exceeding 50% only for about 3.6% of the data. On the other hand, since the INTEGRAL science window typically lasts at least 20 min, there were at least 20 time bins used to compute the $S_V$ value for each science window. We found that for 513 out of 7566 science windows the left side of Equation (2) was positive even for $\sigma_V = 0$, i.e., the observed variability was smaller than purely statistical fluctuations. This indicates that the statistical error of the count rate determined with the OSA software is somewhat overestimated. For a 60 s exposure time a single ISGRI pixel registers usually 0 or 1 count from a source as bright as Cyg X-1. This is the lowest signal-to-noise regime, where the OSA software tends to slightly amplify the statistical errors (see Appendix A in Lubinski 2009 for a discussion).

To estimate this excess we have extracted 1 min light curve for the Crab, a relatively stable source with a count rate level similar to that of Cyg X-1 in the hard state. For the Crab we found that Equation (2) cannot be fulfilled for 2380 out of 5582 science windows. Decreasing the statistical errors by a systematic 1% error reduced this number to 35. We applied the same 1% correction to the Cyg X-1 data, reducing the number of non-determined $\sigma_V$ values to 212 and excluding corresponding cases from a further $S_V$ analysis. The uncertainty

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**Figure 3.** Density map of the $G_H-F_H$ diagram; color coding corresponds to the logarithm of the number of data within a region centered at a given pixel. A larger ellipse above the colorbar shows the size of that region. The vertical dashed lines mark the borders of the six plasma states; the horizontal dashed line marks the hard/soft regime border. The solid line connecting the centers of the two soft state regions is shown together with two examples of the rectangular regions used to compute the density gradient (see the text). The insert shows a density map for the three hard states computed with a finer sampling region (smaller ellipse over the colorbar).
correlations.

Nevertheless, their result for the highest-energy band, variability higher than that of the HS only for the softest data.

The Astrophysical Journal, 100 Hz; however, the data cover only the period from 2005 bands with the SPI detector. Their frequency range was 1 mHz the PH state, lack of correlation for the TH and PS states, and was anticorrelated with the TH state in these two science windows, 161 revolutions in total. The results of this investigation revealed that a coherent variability lasts longer than the revolution period for a majority of data but sometimes there is a jump observed between the two distinct correlation patterns. Thus, the characteristic period of the $I_{\text{HH}} - F_{\text{H}}$ coherence is typically longer than several days. Definitely this issue needs deeper study, which is out of the scope of our paper. Nevertheless, to clean the correlation results from these rapid jumps for each revolution we determined the longest period of an interrupted correlation (or its lack) characterized by the minimum (or maximum) of no correlation probability, neglecting the rest of the data of this revolution. Such a selection was needed for about half of revolutions and the neglected fraction was typically below 20%.

The results of the Spearman test are shown in Figures 4(d) and 5(d), where the single-revolution $I_{\text{HH}} - F_{\text{H}}$ correlation coefficient $r_{\text{S}}$ is plotted against the mean $I_{\text{HH}}$ and mean $F_{\text{H}}$, respectively, for a given revolution or part of it. We do not show the null hypothesis probability $P_{\text{S}}$ in these two figures; however, the points corresponding to $P_{\text{S}} > 0.1$ are marked with circles. The errors in $r_{\text{S}}$ and $P_{\text{S}}$ were computed through Monte Carlo simulations, taking into account the $I_{\text{HH}}$ and $F_{\text{H}}$ uncertainty. Note that the $I_{\text{HH}} - r_{\text{S}}$ and $F_{\text{H}} - r_{\text{S}}$ correlation results

### Table 1

| $I_{\text{HH}}$ | $F_{\text{H}}$ | $S_{\text{V}}$ | $F_{\text{S}}$ | $P_{\text{S}}$ |
|-----------------|----------------|-------------|--------------|-------------|
| $10^{-10}$ erg s$^{-1}$ cm$^{-2}$ | counts s$^{-1}$ cm$^{-2}$ | mJy | mJy |
| Pure hard state ($I_{\text{HH}} < 1.78$) | 33.1% | $[\pm2.0,0.0,0]$ |
| 1.70 ± 0.04 | 158 ± 33 | 5.9 ± 1.8 | 0.35 ± 0.08 | 1.58 ± 0.14 |
| 1.702 ± 0.001 | 156.77 ± 0.02 | 4.8 ± 0.11 | 0.354 ± 0.001 | 1.554 ± 0.002 |
| 1.85 ± 0.04 | 134 ± 24 | 4.7 ± 1.8 | 0.43 ± 0.08 | 1.40 ± 0.14 |
| 1.850 ± 0.001 | 133.60 ± 0.03 | 3.3 ± 0.1 | 0.416 ± 0.001 | 1.368 ± 0.002 |
| Hard intermediate state ($1.93 < I_{\text{HH}} < 2.29$, $F_{\text{H}} > 7.5 < 10^{-10}$ erg cm$^{-2}$ s$^{-1}$) | 18.7% | $[\pm0.4,1.0,0]$ |
| 2.05 ± 0.08 | 114 ± 25 | 5.9 ± 2.4 | 0.56 ± 0.16 | 1.14 ± 0.14 |
| 2.040 ± 0.001 | 110.98 ± 0.03 | 4.0 ± 0.1 | 0.565 ± 0.001 | 1.097 ± 0.001 |
| Soft intermediate state ($1.93 < I_{\text{HH}} < 2.29$, $F_{\text{H}} < 7.5 < 10^{-10}$ erg cm$^{-2}$ s$^{-1}$) | 5.6% | $[\pm0.0,22.3]$ |
| 2.18 ± 0.07 | 49 ± 16 | 12.2 ± 5.5 | 0.50 ± 0.13 | 0.82 ± 0.12 |
| 2.186 ± 0.002 | 49.60 ± 0.05 | 7.3 ± 0.5 | 0.447 ± 0.001 | 0.815 ± 0.002 |
| Transitional soft state ($2.29 < I_{\text{HH}} < 2.65$) | 14.1% | $[\pm0.1,8.1,1]$ |
| 2.47 ± 0.10 | 42 ± 20 | 19.8 ± 7.2 | 0.57 ± 0.20 | 0.79 ± 0.12 |
| 2.450 ± 0.002 | 39.49 ± 0.03 | 12.8 ± 0.5 | 0.487 ± 0.001 | 0.802 ± 0.001 |
| Pure soft state ($I_{\text{HH}} > 2.65$) | 7.0% | $[\pm0.0,22.0,0]$ |
| 2.84 ± 0.14 | 21 ± 10 | 28.4 ± 9.5 | 0.52 ± 0.15 | 0.67 ± 0.09 |
| 2.797 ± 0.005 | 19.59 ± 0.04 | 11.5 ± 0.8 | 0.428 ± 0.001 | 0.661 ± 0.002 |

Note. $I_{\text{HH}}, F_{\text{H}}, S_{\text{V}}$: photon index, flux, and fractional variability amplitude in the $22-100$ keV band, respectively; $F_{\text{S}}$: the $3-12$ keV flux; $P_{\text{S}}$: Spearman rank order test correlation coefficient and null hypothesis (no correlation) probability, for short-term $I_{\text{HH}} - F_{\text{H}}$ correlations. Fraction of time spent in a given state is given in percent in each panel header. Numbers in square brackets are percentage probabilities of transition from a given state to the PH, TH, HI, SI, TS, and PS state, respectively.

of $S_{\text{V}}$ was determined with the bootstrap method, following that of Soldi et al. (2014). Figure 4(b) presents the results of variability analysis where the $S_{\text{V}}$ amplitude is plotted against the $I_{\text{HH}}$ index. To the best of our knowledge this is the first time such a diagram has been constructed with data from the hard X-ray band.

Our analog of the soft X-ray HRD diagram presented in Figure 4(b) extends the findings of Grinberg et al. (2014) to energies above $15$ keV. A complete comparison is not possible because our $S_{\text{V}}$ was extracted for roughly the $0.5-8$ mHz range, whereas their fractional rms was computed for the $0.125-256$ Hz band and their $I_{\text{R}}$ was fitted below $10$ keV. Nevertheless, their result for the highest-energy band, $9.3-15$ keV, looks qualitatively similar to our result in the sense that the minimal variability is observed for medium hardness spectra. The main differences are the location of that minimum (our TH state versus their relatively SS) and their SS variability higher than that of the HS only for the softest data.

An analysis of Cyg X-1 INTEGRAL data in a much broader frequency range was presented by Cabanac et al. (2011), who analyzed variability in the $27-49$, $69-90$, and $96-130$ keV bands with the SPI detector. Their frequency range was $1$ mHz $-100$ Hz; however, the data cover only the period from 2005 March to 2008 May, i.e., the period when Cyg X-1 was almost exclusively in the HS (see Figure 1). The rms amplitude found for that period increases with the spectral hardness (see Figure 4 of Cabanac et al. 2011), in agreement with our results shown in Figure 4(b).

The intra-state $I_{\text{HH}} - S_{\text{V}}$ correlation results presented in Table 2 confirm the trends seen in Figure 4(b), i.e., anticorrelation in the PH state, lack of correlation for the TH and PS states, and positive correlation for the other three states. For the $F_{\text{H}} - S_{\text{V}}$ pair the situation is different: correlation for the PH state and clear correlation for TH state changing into strong anticorrelation for the next three states and no correlation for the PS state.

#### 3.3.2. Short-term $I_{\text{HH}} - F_{\text{H}}$ Correlations

Inspecting the single-revolution data we noticed a clear and common $I_{\text{HH}} - F_{\text{H}}$ correlation, not seen only for the two pure states. To explore this topic we applied the Spearman rank-order test to the $I_{\text{HH}} - F_{\text{H}}$ data for each revolution with at least 10 science windows, 161 revolutions in total. The results of this investigation revealed that a coherent variability lasts longer than the revolution period for a majority of data but sometimes there is a jump observed between the two distinct correlation patterns. Thus, the characteristic period of the $I_{\text{HH}} - F_{\text{H}}$ coherence is typically longer than several days. Definitely this issue needs deeper study, which is out of the scope of our paper. Nevertheless, to clean the correlation results from these rapid jumps for each revolution we determined the longest period of an interrupted correlation (or its lack) characterized by the minimum (or maximum) of no correlation probability, neglecting the rest of the data of this revolution. Such a selection was needed for about half of revolutions and the neglected fraction was typically below 20%.

The results of the Spearman test are shown in Figures 4(d) and 5(d), where the single-revolution $I_{\text{HH}} - F_{\text{H}}$ correlation coefficient $r_{\text{S}}$ is plotted against the mean $I_{\text{HH}}$ and mean $F_{\text{H}}$, respectively, for a given revolution or part of it. We do not show the null hypothesis probability $P_{\text{S}}$ in these two figures; however, the points corresponding to $P_{\text{S}} > 0.1$ are marked with circles. The errors in $r_{\text{S}}$ and $P_{\text{S}}$ were computed through Monte Carlo simulations, taking into account the $I_{\text{HH}}$ and $F_{\text{H}}$ uncertainty. Note that the $I_{\text{HH}} - r_{\text{S}}$ and $F_{\text{H}} - r_{\text{S}}$ correlation results
presented in Table 2 were also computed for the revolution-averaged data because $r_S$ is always computed for a single revolution, not a single science window. On the other hand, the $G_H$–$F_H$ correlation parameters in Table 2 are the long-term results, computed for all data for a given state. The difference between the PH state results and the TH, HI, SI, and TS state results is striking. For the PH state positive, missing, and negative correlations are possible and the non-correlation probability $P_S$ is quite high (see Table 1). For data with $\Gamma_H$ between 1.78 and 2.65 there is a dramatic change: a clear positive correlation ($r > 0.4$) is seen and the null hypothesis probability is usually close to 0. For the PS state the correlation vanishes, consistent with a trend of a decreasing $G_H$–$F_H$ coherence, observed already for the TS state (see also Tables 1 and 2). Concluding, both the PH and PS states are characterized by a vanishing short-term $G_H$–$F_H$ correlation. This extends a definition that can be found in the literature (e.g., Wilms et al. 2001) identifying them with a missing (PH) or completely dominating (PS) disk component in the soft X-ray spectra.

### 3.4. Hard X-Ray–Radio Correlations

A large set of high-quality data in the 22–100 keV band allows us to investigate correlations between the hard X-ray properties and the radio emission from Cyg X-1 in an unprecedented way. A much higher sensitivity above 20 keV was reached only with the CGRO/OSSE detector and currently with the NuSTAR satellite; however, their total exposure time...
spent on Cyg X-1 observations was several orders of magnitude shorter than that of ISGRI. In addition, since the continuous ISGRI observations are separated only by several minutes, there are many science windows that are truly contemporaneous to the radio observations. The radio emission is sizably affected by the orbital modulation effect (e.g., Zdziarski 2012). Using the ephemeris data of Gies et al. (2008) we have tested that the RT and AMI data show a general modulation trend when plotted against the orbital phase. This modulation can be well approximated by a sinusoid with a relative amplitude of about ±15%, very similar to that of Zdziarski (2012). We have applied this correction to the radio data.

In Figures 4(c) and 5(c) we present the 15 GHz flux $F_R$ as a function of the photon index $\Gamma_H$ and hard X-ray flux $F_H$, respectively. The simultaneity criterion was the radio observation time being within the ISGRI observation period of a given science window. If there were several radio observations within that period, the radio flux was computed as a weighted mean. In total, there are 272 ISGRI science windows with contemporaneous radio data. We have tested that loosening the hard X-ray–radio simultaneity criterion from zero to several hours results in an almost unchanged relative data scatter, despite the sample for each state being increased by a factor of several. Therefore it is quite important for the X-ray–radio correlation study to use exactly contemporaneous data.

There is a limiting value of $F_H$ seen in Figure 5(c) around $80 \times 10^{-10}$ erg s$^{-1}$ cm$^{-2}$ separating the high and low radio flux levels. This value of $F_H$ is quite close to the value separating the hard and soft regimes in the $\Gamma_H$–$F_H$ density diagram (Figure 3). The highest radio fluxes are observed for medium-level hard X-ray fluxes, whereas for the highest X-ray fluxes there is a slight anticorrelation between $F_H$ and $F_R$. A similar behavior can be noticed in the literature (Gleissner et al. 2004; Wilms et al. 2006; Zdziarski et al. 2011); however, a pattern of $F_R$ increasing and then decreasing with increasing $F_H$ shown in Figure 5(c) is more clearly visible.

A more interesting correlation/anticorrelation pattern is seen in Figure 4(c) where the radio flux is plotted against the hard X-ray photon index $\Gamma_H$. The general trend of the radio flux dependence on $\Gamma_H$ is quite similar to that shown by Böck et al. (2011), where the 15 GHz flux is plotted against the soft X-ray ($\lesssim 10$ keV) photon index. However, the $F_R$ dependence on the hard X-ray photon index shows some stratification for the three harder states. Radio emission during the PH state varies in a relatively narrow, medium-flux band between 6 and 13 mJy, except for several points. Then, during the TH state $F_R$ varies around a two times higher level. The highest $F_R$ values are observed for the HI state, being on average similar to the TH state but showing the largest radio emission variability (see Table 1). Then, the radio flux slowly decreases with increasing hard X-ray photon index, vanishing above $\Gamma_H = 2.5$. A statistically significant correlation between $F_R$ and $\Gamma_H$ is found for the PH (positive) and HI and TS (both negative) states, as shown in Table 2. A quite strong $\Gamma_H$–$F_R$ anticorrelation appears only for the PH state.

The radio flux $F_R$ plotted in Figure 6 against $S_V$ shows a clear overall anticorrelation, with much stronger hard X-ray variability at very low radio fluxes and slowly decreasing variability with increasing radio emission for IS and HS. It is rather surprising that the strongest flaring radio emission is associated with the weakest plasma variability. Unfortunately, we cannot investigate this issue further: although there were several strong radio flares observed early in the studied period (see Figure 1(g)), they were not exactly contemporaneous to the INTEGRAL observations. When individual plasma states are considered, only the HI state shows a very strong $S_V$–$F_R$ anticorrelation (see Table 2).
The six plasma states exposed by the $\Gamma_{H}/F_{H}$ density diagram in Figure 3 are separated with a high degree of confidence, as demonstrated in Section 3.2, except for the HI state. The dependence of the four other parameters on $\Gamma_{H}$ presented in Figure 4 shows mostly a smooth transition between the neighboring states, except for the PH and PS states. To reveal the differences between the states in a quantitative way we determined the average values of various parameters for each state, listed in Table 1. The weighted mean values confirm the distinct character of each state, in particular confirming strongly a peculiarity of both pure states. The most convincing are the correlation parameters presented in Table 2, revealing with high statistical credibility a distinct dynamical character of each state. For example, $\Gamma_{H}$ and $S_{V}$ are very strongly anticorrelated for the PH state, for the TH state these two parameters are completely independent, and for the HI state a strong positive correlation appears. Table 2 provides several cases of compelling evidence for changing correlation patterns for each pair of the two adjacent states. Besides the physical differences of the six plasma states we examined also their repetitiveness. As shown in Figure 1(e), between MJD 52626 (2002 December) and MJD 55342 (2010 May) Cyg X-1 was mostly in the PH state and then it returned to the same state for MJD 57536–57814 (2016 May–2017 March). The stability of the PS state is less evident due to less abundant and more scattered data. Its broad peak in Figure 3 is formed mainly by data from MJD 55527–55547 (2010 December) but Cyg X-1 was observed in this state also during other periods, mostly in 2013 and in November 2017. The system returns also to the other plasma states after long breaks. Only the SI state was observed by INTEGRAL during a relatively short period of four years, appearing at the end of 2011, 2013, 2014, and 2015, i.e., during major transitions between the HS and SS states. Transitions between the six plasma states are rare and rapid because, as we tested, the single-INTEGRAL-orbit data usually occupy a single-state region. To explore this point on an hour-scale period we computed the numbers of state transitions, assuming a minimal $\Gamma_{H}$ change of 0.05, i.e., larger than the typical uncertainty of majority of our data. The transition occurrence percentages for each plasma state are presented in Table 1. There were 816 transitions found out of 7820 science windows, i.e., the overall state transition probability was around 0.1. The transition probability increases with spectral softness; however, for the two softest states the $\Gamma_{H}$ uncertainty is larger, potentially causing a false detection. The most characteristic feature of the state transition is that they appear almost always between adjacent states. The PH state shows the highest stability (2% transition probability) and the smallest $\Gamma_{H}$ changes, whereas all three SSs are quite unstable (27, 20, and 22% transition probability, respectively). These results agree with the conclusion about the stability of Cyg X-1 spectral states monitored by ASM and MAXI (Grinberg et al. 2013).

Another issue tested for the state transition was the flux level at which they occur, depending on the passage direction. For transient BH systems the $q$-track is usually observed, with the hard–soft transition occurring at much higher flux levels than the soft–hard transition. In our data we have not found evidence for such behavior: differences in the mean $F_{H}$ flux for both transition directions are much smaller than the standard deviation of that mean for each pair of states.

### 3.5. State Credibility and Stability

The six plasma states exposed by the $\Gamma_{H}/F_{H}$ density diagram in Figure 3 are separated with a high degree of confidence, as demonstrated in Section 3.2, except for the HI state. The dependence of the four other parameters on $\Gamma_{H}$ presented in Figure 4 shows mostly a smooth transition between the neighboring states, except for the PH and PS states. To reveal the differences between the states in a quantitative way we determined the average values of various parameters for each state, listed in Table 1. The weighted mean values confirm the distinct character of each state, in particular confirming strongly a peculiarity of both pure states. The most convincing are the correlation parameters presented in Table 2, revealing with high statistical credibility a distinct dynamical character of each state. For example, $\Gamma_{H}$ and $S_{V}$ are very strongly anticorrelated for the PH state, for the TH state these two parameters are completely independent, and for the HI state a strong positive correlation appears. Table 2 provides several cases of compelling evidence for changing correlation patterns for each pair of the two adjacent states. Besides the physical differences of the six plasma states we examined also their repetitiveness. As shown in Figure 1(e), between MJD 52626 (2002 December) and MJD 55342 (2010 May) Cyg X-1 was mostly in the PH state and then it returned to the same state for MJD 57536–57814 (2016 May–2017 March). The stability of the PS state is less evident due to less abundant and more scattered data. Its broad peak in Figure 3 is formed mainly by data from MJD 55527–55547 (2010 December) but Cyg X-1 was observed in this state also during other periods, mostly in 2013 and in November 2017. The system returns also to the other plasma states after long breaks. Only the SI state was observed by INTEGRAL during a relatively short period of four years, appearing at the end of 2011, 2013, 2014, and 2015, i.e., during major transitions between the HS and SS states. Transitions between the six plasma states are rare and rapid because, as we tested, the single-INTEGRAL-orbit data usually occupy a single-state region. To explore this point on an hour-scale period we computed the numbers of state transitions, assuming a minimal $\Gamma_{H}$ change of 0.05, i.e., larger than the typical uncertainty of majority of our data. The transition occurrence percentages for each plasma state are presented in Table 1. There were 816 transitions found out of 7820 science windows, i.e., the overall state transition probability was around 0.1. The transition probability increases with spectral softness; however, for the two softest states the $\Gamma_{H}$ uncertainty is larger, potentially causing a false detection. The most characteristic feature of the state transition is that they appear almost always between adjacent states. The PH state shows the highest stability (2% transition probability) and the smallest $\Gamma_{H}$ changes, whereas all three SSs are quite unstable (27, 20, and 22% transition probability, respectively). These results agree with the conclusion about the stability of Cyg X-1 spectral states monitored by ASM and MAXI (Grinberg et al. 2013).

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### 3.6. Hard X-Ray Photon Index Distribution

At the end of this section we explore whether the finding of clustered photon index values could be obtained with other hard X-ray missions. There are several other past or current hard X-ray detectors that can be used for such a study. Among the two CGRO detectors, OSSE and BATSE, only the latter provided a large set of data in a similar energy band. However, its occultation data are of much lower quality than those of ISGRI. The Beppo-SAX mission has provided a rather limited number of pointed observations of Cyg X-1. The same is true for the HXD detector of Suzaku and for the most sensitive hard X-ray detectors ever launched, namely those onboard NuSTAR. On the other hand, the Swift–BAT detector, characterized by a sensitivity similar to ISGRI, observes Cyg X-1 almost every day but its data are affected by a relatively large statistical uncertainty due to the effectively short observing period for a single day. The most promising seems to be an analysis of the RXTE Proportional Counter Array (PCA) and High Energy X-ray Timing Experiment (HEXTE) detectors spectra; however, this is a rather demanding task, beyond the scope of this paper.

Nevertheless, we have chosen the BATSE detector to get some hint about how its results for Cyg X-1 compare to those of ISGRI. Using the BATSE data has allowed us to extend the observing period by nine additional years, namely 1991–2000. The 2703 BATSE daily spectra for that period were analyzed with the power-law model. The uncertainty in the BATSE photon index is almost always larger than 0.05, whereas the corresponding uncertainty in the ISGRI data is almost always smaller than this value. This explains why in our test we obtained a distribution of the BATSE photon index resembling a broad, single Gaussian with an additional tail corresponding to the IS and SS, shown in Figure 7(a). We also checked that selecting subsamples of the BATSE results with lower $\Delta \Gamma_{H}$ values still produces a distribution without any evident clustering.

The comparison between ISGRI and BATSE is also affected by the need to sum up the BATSE occultation data for a single day to improve the quality of the spectra. Any significant intraday variability of the spectral shape can affect the $\Gamma_{H}$ distribution, washing out its discrete features. We have tested the robustness of our results against this concern, repeating the ISGRI spectral modeling for 579 daily summed spectra. As demonstrated in Figure 7(b), the positions of all states’ peaks...
remained almost unchanged when compared with the 2D distribution in Figure 3.

Since the INTEGRAL satellite hosts another hard X-ray instrument on board, the SPI imager, it is possible to test the $\Gamma_H$ clustering with the data taken at the same time as the ISGRI data. We analyzed the SPI spectra with the power-law model in the $22-100$ keV band. The number of SPI spectra is much smaller than that of the ISGRI spectra (due to exclusion of data with photon index uncertainty $>0.1$; see Section 2.1), mostly eliminating the softer states’ data. The SPI sensitivity below 100 keV is lower than that of ISGRI, resulting in an error of $\Gamma_H$ typically around four times larger than the typical ISGRI uncertainty. Such a difference in the quality of the spectral data resulted in a broadened $\Gamma_H$ distribution, see Figure 7(b), similar to that produced with the BATSE data. To check the effect of the smearing of the distribution due to a large $\Gamma_H$ uncertainty, we applied a Gaussian blur with a standard deviation of 0.08 to the ISGRI data. The resulting distribution is presented with a black histogram in Figure 7(b), clearly showing that a high-precision determination of the photon index is crucial to uncovering its clustering for Cyg X-1.

4. Discussion

4.1. Spectral and Plasma States of Cyg X-1

A classification of the plasma states based on $\Gamma_H$ should be confronted with a conventional spectral state selection based on the soft X-rays. In Figure 8 we present a comparison of our state selection with the state definitions of Grinberg et al. (2013) derived with the ASM and MAXI monitors. Since the energy band and quality of monitoring data are both limited, when compared to the spectra from the soft X-ray telescopes, the state classification of Grinberg et al. (2013) was based on a comparison with the results of contemporary RXTE/PCA observations. For ASM this gave a good selection of the SS and HS, whereas the IS was contaminated up to 10%. Selection criteria applied to the MAXI data were more conservative as shown in Figure 8 where the IS region for MAXI is narrower than the corresponding region for ASM.

We explored the numbers of the SS, IS, and HS selections according to the Grinberg et al. (2013) criteria for ASM and MAXI data contemporary to INTEGRAL data and classified by a range of the hard X-ray photon index, i.e., data shown with colors in Figure 8. We observe similar trends as those found by Grinberg et al. (2013), when comparing the all-sky monitor state selection with that based on spectral fitting. The PH state data are practically always classified as the HS. The same happens for the TH state for the MAXI-based selection, whereas for the ASM data we found about 20% data classified...
as the IS. The HI state is mostly also intermediate with the ASM-based selection but a majority of the HI data fall outside the narrow region of the IS defined with the MAXI criteria. The SI state data are mostly found in the SS region, 67% for ASM and 90% for MAXI. Both TS and PS states data are almost always classified as the SS with the ASM and MAXI criteria.

As mentioned in Section 1, the most reliable state classification is obtained when the spectral slope can be determined directly from the spectra or from monitoring data converted into fluxes in several bands. The second approach was developed, e.g., by Zdziarski et al. (2002), where the ASM count rates were converted into flux using a redistribution matrix obtained through a comparison with contemporary PCA spectra. We applied the same procedure to the ASM daily averaged data, using the same matrix and determining fluxes in the three energy bands: 1.5–3.0 keV, 3.0–5.0 keV, and 5.0–12.0 keV. With the last two values we determined the photon index in the 3.0–12.0 keV band, \( \Gamma_{\text{soft}} \). In the case of MAXI we fitted the power-law model to the GSC daily spectra, obtaining directly the photon index in the same energy band. The \( \Gamma_{\text{soft}} \) results contemporary to the INTEGRAL data are shown in Figure 9, as a function of the hard X-ray photon index \( \Gamma_H \).

The solid line in Figure 9 shows that for the PH and TH states there is an agreement between \( \Gamma_H \) and \( \Gamma_{\text{soft}} \). Data are scattered, at least partly due to the orbital modulated absorption of the soft X-ray emission. For the rest of the data the \( \Gamma_{\text{soft}} \) values are larger than the \( \Gamma_H \) values, which can be explained by a disk emission component modulating the soft X-ray part of the spectra.

The relation between the soft and hard X-ray photon indices for Cyg X-1 was studied by Wilms et al. (2006) who analyzed the PCA+HEXTE spectra with an absorbed broken power-law model, with the break energy around 10 keV and the \( \Gamma_1 \) and \( \Gamma_2 \) indices fitted below and above that energy, respectively. Their model included also a \( K_{\alpha} \) iron line and an exponential cut-off of the high-energy power-law component. Their results are different from the \( \Gamma_{\text{soft}}-\Gamma_H \) relation shown in Figure 9, with data lying approximately along a single straight line and \( \Gamma_2 \) always smaller than \( \Gamma_1 \), an effect that was ascribed to a missing reflection component in their model. The difference with respect to our results can be explained by the fact that our \( \Gamma_H \) corresponds to effectively larger energies than the \( \Gamma_2 \) fitted by Wilms et al. (2006) because the combined PCA+HEXTE spectra are statistically dominated during the fit by high-quality PCA data below 30 keV. Thus, \( \Gamma_2 \) is probing the reflection peak range whereas \( \Gamma_H \), fitted above 22 keV, is less affected by the reflection component. The soft X-ray photon index \( \Gamma_1 \) of Wilms et al. (2006) and Grinberg et al. (2013, 2014, who included the disk component in their model) also cannot be directly compared with our \( \Gamma_{\text{soft}} \) index. Interestingly, the range of their \( \Gamma_1 \) values is practically the same as for our \( \Gamma_{\text{soft}} \), namely between 1.6 and 3.4. The 3–12 keV band is almost not affected by absorption and for the HS the disk, reflection, and iron line components are weak. Thus, for the hardest data \( \Gamma_1 \) and \( \Gamma_{\text{soft}} \) should be very similar.

Spectral state classification based on the soft X-ray results, either count rates or fluxes, cannot reveal the six states found with the \( \Gamma_H \) photon index. Figures 8 and 9 demonstrate that the PS, TS, and SI states occupy a similar range of the soft X-ray parameters. The same holds for the three harder states except for the HI state, roughly traceable through the \( \Gamma_{\text{soft}} \) values. In fact, the definitions of the IS based on the soft X-ray photon index adopted by Zdziarski et al. (2002) (see the horizontal lines in Figure 9) and Grinberg et al. (2013) (2.0 < \( \Gamma_1 \) < 2.5) are consistent only with our HI state.

Pottschmidt et al. (2003b) found that in 1998 May the source switched from a typical HS observed earlier with RXTE to a slightly softer HS. This new HS exhibited different variability patterns, with a smaller rms amplitude and relatively frequent, failed, or successful transitions to the IS or SS. Since the Pottschmidt et al. (2003b) observations were done before the INTEGRAL launch, we cannot verify if their bimodal character of the HS corresponds to our PH and TH states.

An energy-resolved analysis of Cyg X-1 variability with the RXTE data taken over the period 1999–2011 (Grinberg et al. 2014) partly covers the period analyzed by Pottschmidt et al. (2003b). This new study confirmed a distinct character of the variability (rms, time lags) observed for the hardest spectra, with \( \Gamma_1 < 1.75 \). As mentioned above, for the hardest data \( \Gamma_1 \) and \( \Gamma_{\text{soft}} \) should be very similar, justifying the identification of the hardest data of Grinberg et al. (2014) with the PH state. A much smaller set of Cyg X-1 RXTE data was also analyzed in terms of a cross-correlation function (CCF) between the photon index and the 3–20 keV count rate at 100 ms time resolution (Skipper et al. 2013). They found that there is an evolution of the CCF from a correlation seen for the hardest spectra changing into an anticorrelation for the rest of the HS spectra.

In Section 1 we mentioned that Cyg X-1 varies in a quite limited region of the HID diagram when compared to systems undergoing transitions. Our finding is that also in the hard X-ray diagram we do not see a hysteresis: transitions between the states in both directions happen at the same flux level. However, similarly to the transients we found two distinct ISs, hard and soft. To our best of our knowledge, bimodality of the IS is almost not explored for Cyg X-1 because in the soft X-rays the HI state just forms the canonical IS, whereas the SI state falls into the SS region (see Figure 9). Presumably such a bimodality is seen in the time lags, where for 2.1 < \( \Gamma_1 \) < 2.7 the lags are much larger than for the rest of the SS \( \Gamma_1 \) range (Grinberg et al. 2014), possibly exposing the SI state. This is characterized by a clearly smaller rms amplitude and is seen in Figures 3 and 4 of Grinberg et al. (2014). A similar effect was...
already observed by Pottschmidt et al. (2003b) during failed transitions. At hard X-rays we found the opposite behavior: variability amplitude $S_V$ for the HI state is clearly smaller than for the SI state (see Table 1). The radio emission is rather weak for the SI state and very strong with flares for the HI state, in agreement with the SIMS and HIMS characteristics (Belloni & Motta 2016). Another similarity is that our HI state occupies quite a wide range of $\Gamma_{HI}$ as the HIMS does for the hardness ratio, whereas the SI and SIMS regions are quite narrow (see Figure 3.7 of Belloni 2010).

The PS state term is used for the spectral state dominated in the soft X-ray band (<20 keV) by the disk emission (Wilms et al. 2001). Although the state selection adopted in Filothodoros et al. (2018) does not completely correspond to the six states found here, for a summed INTEGRAL spectrum of the softest Cyg X-1 data they found the hard/soft compactness ratio, $l_h/l_s$, and optical depth of the plasma sharply smaller than the corresponding values for the rest of the SS spectra. Thus, spectral analysis with a hybrid Comptonization model is consistent with a separation of the PS state through the $\Gamma_{HI}$-$F_{HI}$ diagram.

4.2. System Geometry

Provided that the dominant process shaping the hard X-ray continuum of BHBs is inverse Comptonization on thermal electrons, a primary driver of the spectral slope in that band is the system geometry considered in terms of the Compton amplification strength (Haardt & Maraschi 1991; Stern et al. 1995). This amplification can be either modeled directly through a certain parameter of a given implementation of the Comptonization or derived from fluxes of the seed photons and Comptonized component. It has been demonstrated many times that the photon index strongly correlates with the Compton parameter $\Gamma$, compactness ratio $l_h/l_s$, or the Compton amplification factor (e.g., Malzac 2001; Wilms et al. 2006; Gierliński et al. 2010). Therefore, $\Gamma_{HI}$ can be used as a tracer of the system geometry.

The distribution of $\Gamma_{HI}$ values found by us for the three harder states is similar to those found for Seyfert nuclei (Lubiński et al. 2016). The PH and TH state peaks correspond to radio-quiet Seyferts, having the hardest X-ray spectra and weak or moderate radio emission. On the other hand, several radio-loud objects of Lubiński et al. (2016) sample exhibit softer spectra resembling the HI state of Cyg X-1. Both photon index distributions, that of Cyg X-1 and that of Seyferts, show an abrupt cut-off below $\Gamma=1.7$ (see Figure 3 of Lubiński et al. 2016), i.e., just below the main peak.

Interestingly enough, such a peak of $\Gamma$ around 1.7 can be justified on theoretical grounds. In their study of the synchrotron boiler effect, Malzac & Belmont (2009) found that assuming an initially non-thermal distribution of plasma electrons in the absence of an accretion disk, a quasi-thermal Comptonization continuum can be obtained for a wide range of the plasma compactness, with the photon index close to 1.7. Also their range of $kT_e$ values, concentrated between 30 and 50 keV, is similar to that observed for both the HS of Cyg X-1 (Zdziarski et al. 2002; Del Santo et al. 2013) and hard spectral Seyferts (Lubiński et al. 2016). A similar result with a stable spectral slope was obtained by Poutanen & Vurm (2009), who also investigated the synchrotron boiler effect for an initially non-thermal plasma. Therefore, the PH state of Cyg X-1 can be interpreted as a limiting mode of accretion dominated by a hot compact plasma, with a negligible interaction with the accretion disk, probably truncated at large radii. The seed photons undergoing Comptonization are produced by synchrotron radiation of the electrons of the plasma region itself (e.g., Veledina et al. 2011; Poutanen et al. 2018). A quite narrow distribution of $\Gamma_{HI}$ (or $\Gamma$), peaking at the same value for Cyg X-1 and Seyferts, can indicate that the system geometry is reaching its physical limit, with the plasma region being concentrated well within the inner radius of the disk.

The PS state can be interpreted as a second limiting geometry of the Cyg X-1 accreting system, with no signature for an autonomous plasma region besides the non-thermal flares and atmosphere of the accretion disk. The PS state data dominate the softest (s1) spectrum analyzed by Filothodoros et al. (2018). That spectrum, with compactness ratio $l_h/l_s$ of 0.04 ± 0.01, is softer than any RXTE spectrum analyzed by Wilms et al. (2006) and Gierliński et al. (2010), with all values of this parameter >0.2. On the other hand, there were extremely soft spectra of Cyg X-1 observed by Suzaku (2010, 2013), contemporary to our PS state. The softest of these was fitted with $l_h/l_s=0.11^{+0.02}_{-0.01}$ (Kawano et al. 2017); however, a closer comparison is impossible, due to several parameters fixed at different values than in Filothodoros et al. (2018) and the Suzaku spectrum fitted in the 0.8–60 keV band, whereas the INTEGRAL spectra were fitted in the 3–200 keV band. The fact that the PH state was not observed with RXTE can be explained by the much larger time spent by Cyg X-1 in the SS in the 2010–2017 period than during the RXTE observations.

In summary, the Cyg X-1 system appears to evolve between the two extreme plasma states with (primarily for the TH state) non-thermal electrons, whereas for the four transient states the plasma is mostly thermal. States change presumably due to the changes of geometry of the plasma–disk system, resulting in a varying cooling of the plasma by the disk photons. The fact that this evolution goes through several distinct plasma states instead of some gradual transformation demands an explanation. Collecting new INTEGRAL data in the coming years will shed more light on the location of these states in the $\Gamma_{HI}$-$F_{HI}$ diagram, especially those less populated. Among the four transient states the most intriguing appears the SI state, showing vertical orientation in Figure 3. This vertical structure has a width comparable with the typical uncertainty of $\Gamma_{HI}$ in this range of the diagram. Thus, the intrinsic scatter of the photon index is presumably quite small, indicating a well defined geometry of the hard-to-soft regime transition, a kind of “bottleneck” mechanism.

Since clustering is observed for both hard and soft regimes, its origin might be a certain common mechanism forming different plasma geometries. A varying accretion rate is thought to be a principal driver of the state transition in binary systems. Nevertheless, even if the system accretes at distinct rates, these rates should be well preserved during the mass transport in the disk. In addition, there should be a tight mechanism of forming specific plasma geometries in reaction to a varying accretion rate. More light on the plasma states in Cyg X-1 will be shed following state-wise broadband spectral analysis with physical models and more advanced timing analysis.
5. Conclusions

We have analyzed INTEGRAL/ISGRI data collected over 15 yr of Cyg X-1 observations, exploring all uninterrupted monitoring periods, lasting typically 0.5–2 hr. This data set comprised almost 8000 pointings for which we have extracted spectra and computed the fractional variability amplitude. Since the emission of Cyg X-1 in the 22–100 keV is unabsorbed and weakly affected by the Compton reflection and high-energy thermal cut-off, even a simple power-law model allows for a reliable characterization of the primary emission from the hot plasma. Using this model we determined the flux $F_H$ and photon index $\Gamma_H$ for the 22–100 keV band. To explore the hard X-ray/radio relation we used the RT/AMI data at 15 GHz. Our main findings are as follows.

1. The $\Gamma_H$–$F_H$ density diagram reveals six distinct regions, concentrated around $\Gamma_H = 1.7, 1.85, 2.0, 2.2, 2.5$ and 2.8, with a relative population of 33%, 21%, 19%, 6%, 14%, and 7%, respectively. These six plasma states of Cyg X-1 were named, accordingly, pure hard, transitional hard, hard intermediate, soft intermediate, transitional soft, and pure soft. Such clustering is observed for the first time for any BH binary.

2. Each of the six plasma states exhibits a different range of variability measured with the fractional variability amplitude $S_V$. In the three softer states the mean $S_V$ is typically $\gtrsim 10\%$, whereas for the three harder states it is typically $\lesssim 5\%$, reaching minimal values for the transitional hard state. Our results extend to higher energy the findings of Grinberg et al. (2014), who found for Cyg X-1 a minimal variability for medium-hardness data at several energy bands below 15 keV. This trend is different from the typical behavior observed in soft X-rays for transient BHBs, where the variability increases monotonically with the spectral hardness.

3. The radio flux $F_R$ at 15 GHz is correlated with all three hard X-ray observables. An overall correlation with the maximal radio fluxes seen for an intermediate range of hard X-ray flux and spectral slope values was already reported for Cyg X-1. However, the radio flux plotted against the hard photon index occupies different levels for all six states. In addition, we found that the radio flux decreases with increasing hard X-ray variability amplitude $S_V$.

4. We have confronted our plasma states with the standard spectral states selected using the softer X-ray bands. We identify the pure hard and transitional hard states with the two hard states found by Pottschmidt et al. (2003b) and Grinberg et al. (2014), both using soft X-rays. A distinction between the two intermediate states for Cyg X-1 is made for the first time; they appear to be counterparts of the hard intermediate and soft intermediate states observed typically for BHB transients. The pure soft state was identified within the soft state through its specific hard X-ray variability.

5. Under the assumption of the Comptonization process as a primary source of the hard X-ray radiation our results can be interpreted in terms of six distinct geometries of the plasma region in Cyg X-1. The hardest and softest states show no hour-scale $F_H$–$\Gamma_H$ correlation, suggesting a lack of plasma–accretion disk interaction. The other four states exhibit strong correlation, slowly decreasing with increasing $\Gamma_H$, presumably due to decreasing inner radius of the disk.

6. Our results for the pure hard state agree with the predictions of the synchrotron boiler models, with primarily non-thermal hot electrons Comptonizing their own synchrotron radiation. Such models predict also a narrow distribution of the photon index for a broad range of the system parameters, in agreement with our findings.

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Software: OSA v10.2 and 11.0 (Courvoisier et al. 2003), mxproduct (Matsuoka et al. 2009), HEAsoft (HEASARC 2014), XSPEC (v12.9.0; Arnaud 1996).

Appendix A

Separation of the Two Soft States

The number of $\Gamma$–$F_H$ data missing in the valley between the TS and PS states was determined using rectangular regions with the longer side perpendicular to the line connecting the centers of these two regions (see Section 3.2 and Figure 3). Figure A1 presents the number of data points found for rectangular regions centered at $\Gamma_H$ between 2.28 and 3.0, with a step of 0.04. The null hypothesis probability (i.e., a single SS) was tested with the three density models: Gaussian, log-normal, and super-Gaussian fitted to the rectangular regions’ data. The super-Gaussian is a flat-top Gaussian, where the standard Gaussian exponent argument is raised additionally to some power; in our case it was set to $2$: $f(x) \propto \exp\{-[(x - x_0)^2/(2\sigma^2)]^2\}$. The $\chi^2$-test values for
the log-normal, Gaussian and super-Gaussian models are 62.4, 64.5, and 73.4, respectively, corresponding to $p$-values of $2 \times 10^{-7}$, $9 \times 10^{-8}$, and $<10^{-8}$, respectively, for 16 degrees of freedom. The valley between the TS and PS states is seen at $I_H$ around 2.6. For all tested models at least 60 data points are missing in the valley and must be shifted to either the TS state ($I_H \approx 2.5$) or to the PS state ($I_H \approx 2.78$) peaks.

Appendix B
Clustering Test with the Eqpair Model

To simulate a set of realistic spectra we used the results of Filothodoros et al. (2018) who fitted the hybrid Comptonization model eqpair to the JEM-X and ISGRI spectra of Cyg X-1 in the 3–200 keV band. Their spectra were grouped according to the 40–100/22-40 keV hardness found for Cyg X-1 by Filothodoros et al. (2018) who nearly exponential, with log$(I_H/l_H)$ between $-0.9$ and $1.3$. Using their results we found that the dependence of the five other main eqpair parameters on log$(I_H/l_H)$ is practically linear, separately for the HS and SS. Values of these parameters were computed for 170 log$(I_H/l_H)$ channels in the [0.45,1.3] range for the HS, and for 200 log$(I_H/l_H)$ channels in the $[-0.9,0.1]$ range for the SS. These five parameters are (within the limits found for the HS and SS, respectively, given in parenthesis): Thomson scattering depth of the plasma (1.52–0.88, 0.7–0.12), non-thermal/thermal power ratio (0.78–0.51, 0.57–0.31), index of the non-thermal electrons’ power-law distribution (2.04–2.25, 2.13–3.74), Compton reflection strength (0.14–0.6, 1.81–3.42), and the seed photon temperature (150 eV, 150–300 eV). For each simulation we have randomly chosen a spectrum from our 7821 spectra for each of the HS and SS regimes. The 22–100 keV flux for each channel was randomized with a normal distribution, approximating the 2D density map is shown in Figure B1, with a smooth distribution of density for both the HS and SS regimes. We tested various modifications of the functions approximating the dependence of the eqpair parameters on log$(I_H/l_H)$. Only small (<10%) and broad density maxima are occasionally observed. We did not obtain an artificial aggregation of the photon index resembling the six plasma states shown in Figure 3.

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