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Physical characterization of the corona at the black hole candidate 1E 1740.7-2942

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Abstract. One of the most straightforward ways to explain the hard X-ray spectra of X-ray binaries is to assume that comptonization of soft photons from the accretion disk is occurring. The region in which this comptonization takes place, called the corona, is characterized by only two parameters: its thermal energy kT and its optical depth τ. Hard X-ray spectra analysis is the tool in diagnosing the behavior of these parameters. But the lack of consistency in obtaining/analyzing long-term databases has hindered the characterization of the corona in X-ray binaries with black holes. With the aim of better understanding such behavior for the black hole candidate 1E 1740.7−2942, we performed a homogeneous analysis for a large data set from the ISGRI telescope on-board the INTEGRAL satellite. Modeling a large number of hard X-ray spectra of 1E 1740.7−2942 with widely accepted models allowed us to derive the system's most recurring corona temperature ($kT = 44 \pm 18$ keV) and optical depth ($\tau = 1.5 \pm 0.6$).

Resumo. O espectro de raios X em binárias de raios X pode ser explicado diretamente pela comptonização de fótons de enegias mais baixas originados, por exemplo, em um disco de acréscimo. Tal comptonização, em binárias com buracos negros, ocorre em uma região que chamamos de coroa. A coroa é caracterizada somente por dois parâmetros: sua energia térmica kT e sua profundidade óptica τ. Nós fazemos uso da análise espectral em raios X duros ($E > 20$ keV) para estudar estes dois parâmetros. A falta de consistência na obtenção/análise de bases de dados longas para um mesmo objeto, tem impedido que tais parâmetros sejam consistentemente estudados. Com o objetivo de caracterizar a coroa no candidato a buraco negro 1E 1740.7−2942 nós procedemos com uma redução/análise de dados uniforme (em parte) da extensa base de dados produzida pelo telescópio IBIS a bordo do satélite INTEGRAL. A análise espectral foi feita com o ajuste, a cada espectro individual, de uma série de modelos que são amplamente usados na literatura, permitindo-nos derivar os valores da temperatura da coroa ($kT = 44 \pm 18$ keV) e da profundidade óptica ($\tau = 1,5 \pm 0,6$).

Keywords. Accretion, accretion disks – Black hole physics – Methods: observational – Space vehicles: instruments – X-rays: binaries

1. Introduction

The subject of this study is the hard X-ray spectra of a black hole candidate in a (supposed) X-ray binary. The source 1E 1740.7−2942, our target, was discovered by the Einstein satellite (Hertz & Grindlay 1984). Its truly nature as a binary X-ray source is not yet decided/verified, since we have no counterpart to the source in longer wavelengths, an observational evidence commonly attributed to the high extinction in these longer wavelenghts to the direction of the Galactic Center (GC), where the source is located. It is also, in our opinion, disputable the common classification of the source as belonging to the class of the low mass X-ray binaries (LMXB), as discussed in one of our studies on the source (Stecchini et al. 2017), where we suggest that the source is a high mass X-ray binary (HMXB). In that same study we revisited (and confirmed) the 12.6 d (likely being the) source's orbital period. The source is traditionally listed as one of the brighter sources in the GC region, a fact that we also have verified (Leão et al. 2020): sometimes it **is** the brightest source in the field, but most of the time it is not, fitting perfectly with one of the best well-known features of X-ray binaries, i.e., variability. Its hard X-ray nature (i.e, the source is brighter in hard X-rays, $E > 20$ keV), besides being discovered by a soft X-ray imaging telescope ($E < 20$ keV), is known since the first monitoring of the GC by a coded-mask imaging telescope, the SL2-XRT telescope (Skinner et al. 1987), onboard SpaceLab (our first home in the space, i.e., the first space station which orbited the Earth). Another long monitoring, by the Russian/French mission GRANAT, performed by two telescopes ART-P (Siuniaev et al. 1990) and SIGMA (Roques et al. 1990), has further confirmed the hard X-ray nature of 1E 1740.7−2942 (Sunyaev et al. 1991) as well as discovered the 3 main spectral states of the source. By an immediate analogy with the spectral states of Cyg X-1, the first and classical (stellar mass) black hole discovered, 1E 1740.7−2942 was classified as a black hole, i.e., more specifically as a black hole candidate, since no dynamical measurement of mass is available to the source. The hard X-ray spectra of black hole in X-ray binaries can be explained by several models. In this particular study, we will make use of the *Sombrero* model (Gilfanov 2010). In this model, soft X-ray photons are up-scattered to hard X-rays, due to inverse Compton scattering, i.e., the scatter of photons by electrons, in a plasma that surrounds the inner regions of the black hole and the accretion disk. This region is refereed as the black hole corona, or simply, the corona. Within the context of the Sombrero model, any part of the soft X-ray spectrum of a black hole is due to the accretion disk (and thermal by nature) and the hard X-ray portion is due to the corona. The transitions between the spectral states are due to a truncation radius in the disk: when the (inner) disk (radius) is truncated at distances closer to the ISCO (inner stable circular orbit), the hard X-ray part of the spectrum vanishes. When the disk is truncated at larger distances, the hard X-ray part of the spectrum arise. The transition between the two states is generally driven by the emission of a radio jet. We caution the reader that this picture has been confirmed observationally for several sources, as well as been refuted for some others. The sombrero model also explains another component of the X-ray spectrum of black hole, the reflected component, which can be used, along with the thermal (soft) part of the spectrum for mass estimates. Our group has also done a study in this subject (Stecchini et al. 2020). Our goal here is to characterize the corona in 1E 1740.7−2942: we will provide the corona's temperature kT and its optical depth τ. We have done that by using a systematic data reduction/analysis on a large database collected by the INTEGRAL (Winkler et al. 2003) satellite. In the coming sections we will present our database, explain our methods and show our results and conclusions.

2. Data Selection, Analysis and Results

From the database of the ISGRI telescope (Lebrun et al. 2003), we selected, for this study, all the observations in the 2003–2012 time-span, resulting in 314 observations. Among those, 43 did not have a signal-to-noise-ratio (SNR) greater than 5, in the 20–200 keV range, and are not considered. A previous version of this study was already published (Stecchini et al. 2021) where our sample, for the same time-span, had a total of 184 observations. In this present study, through a more robust data reduction script, we were able to recover observations that were previously discarded. In the present study we have increased our sample from 184 to a total of 255 observations. We will show these numbers in better detail in the coming lines.

The data reduction script makes use of a cooking book with recipes for ISGRI data reduction to produce a final spectrum for each observation (or revolution, in INTEGRAL language). The script also produces several lightcurves in several bands (not used here) and provides the user (accordingly to the cooking book recipes) the appropriate response functions for data analysis. Each revolution/observation takes, on average, ∼ 8 h to be reduced (in a standard PC). As we have already said, from the 314 observations present in ISGRI database, after this step we are left with 271 after due to the rejection of 43 revolutions based on the SNR. It was here, in this step, the big gain in number-of-observations when compared (to the same time-span) to our previous study (Stecchini et al. 2021), since we recovered 71 (out of 86) revolutions.

We then fit to those 271 observations, trough an automatic script for data analysis. We used a set of predefined models that are widely used to fit the spectra of black hole X-ray binaries (Castro et al. 2014). The script fits automatically spectra in the 20–200 keV band, with the aid of XSPEC (Arnaud 1996). Two models among the several available in XSPEC are of particular importance here: (in XSPEC language) `compTT` (Titarchuk 1994) and the simple `powerlaw`. After fitting the 271 spectra with these two models, we have to discard 16 observations, due to rejection by our adopted statistical figure-of-merit (we use the widely used χ^2). We are, then, left with 255 observations.

So, here, in this present study, we increased our previous database from 184 to 255 observations, when comparing the same time-span (Stecchini et al. 2021), an increase of almost 39%. In Fig. 1 we show a spectrum of 1E 1740.7−2942 to illustrate the whole data reduction/analysis procedure

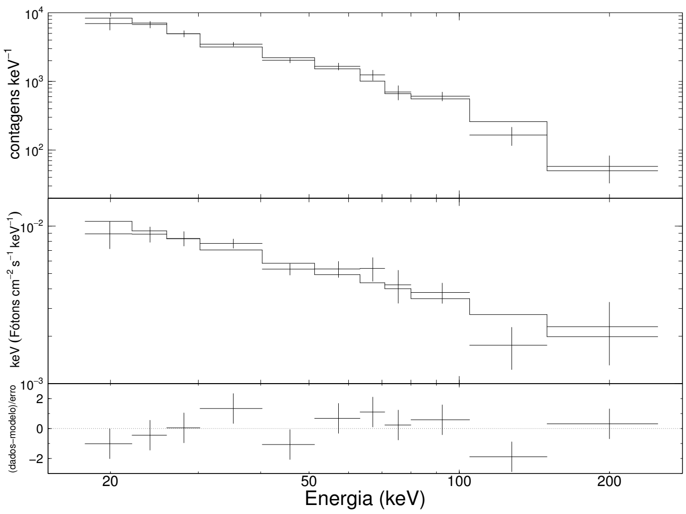

Figure 1. Spectrum of 1E 1740.7−2942 for the revolution number 1155 (according to INTEGRAL naming rules for observations/revolutions). The upper panel shows the spectrum of the source, in instrumental units (i.e., counts) for the 20–200 keV range: this is the result of the data reduction script. At the middle panel, after model convolution as well as response function correlations, we can show the spectrum in physical units (i.e., photons): this is the result of the data analysis script. The model used for the production of this panel was a simple powerlaw. The lower panel show the residuals of the fit, in appropriate units, from where e.g., the statistical figure-of-merit of the fit can be derived: for this particular fit, the $\chi^2_{\rm reduced}$ is equal to 1.1.

Here we can show the first result of our study. The powerlaw, as the name indicates, is obtained by fitting a simple powerlaw to a given spectrum, i.e.,

$$F(E) = F_0 \times \left(\frac{E}{E_0}\right)^{\Gamma_{\rm pl}} , \qquad (1)$$

where F_0 is the normalization flux at a given energy. Here we choose properly F_0 at the E_0 of 20 keV (i.e., as a result of the fit, XSPEC will return F_0 as well as the powerlaw index). This index is widely used in the literature (Remillard & McClintock 2006) to specify when a given black hole in a X-ray binary was observed in the hard X-ray state, one of the observed spectral states for these sources. Typical values, from the previously cited study, are 1.4–2.1, where, in Fig. 2 we show that, for 1E 1740.7−2942, the hard X-ray state is observed with $\Gamma_{\rm pl}$ in the range 1.1–2.4. This spectral state is the canonical state for 1E 1740.7−2942, i.e., the preferred spectral state for the source, a fact that our team have already observed (Stecchini et al. 2017).

When the fit with `compTT` is performed, we store the two parameters of the fit: the corona's temperature (kT) and the optical depth, τ (due to electrons and integrated in the the 20–200 keV range). Nevertheless, we have performed the `compTT` fit with *extremely* and extra care. When using the `compTT` model-fitting in XSPEC, the user is advised to verify if the return parameters of the fit, kT and τ, are within some constrained regions, where the numerical solution used in the fit is valid. We want to emphasize that this is generally a forgotten security measure, so to say, taken by users of `compTT` in XSPEC. These constrained regions are obtained (Hua & Titarchuk 1995) by calculating a β factor (which depends uniquely of τ),

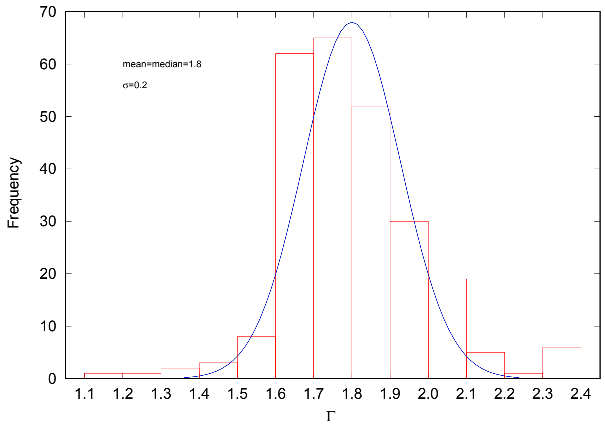

Figure 2. The histogram of the Γ_{pl}, obtained from Equation (1), for our database of 255 observations of the INTEGRAL database on 1E 1740.7−2942 from 2003 to 2012. As can be seen in the Figure, the hard X-ray spectral state is well observed when the index is within the 1.1–2.4 range (see text for details).

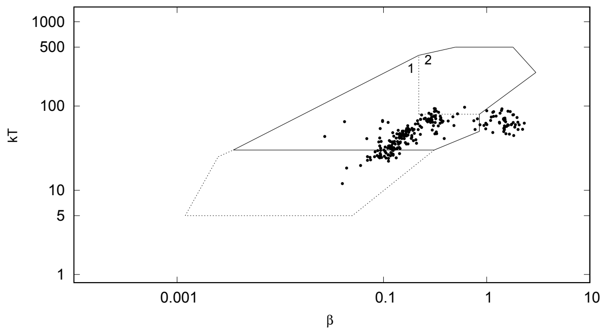

Figure 3. For using the `compTT` model in XSPEC, the user is advised in making the above plot. The plot shows regions delimited by solid and dashed lines. Outside those regions, according to the literature (Hua & Titarchuk 1995), the numerical solution used in `compTT` is not valid. We have calculated β (see the text for its formulae) and, as can be seen in the Figure, we have to discard 64 out of our 255 observations.

$$\beta = \frac{\pi^2}{12\,(\tau + 2/3)^2}\left(1 - e^{-1.35\tau}\right) + 0.45\,e^{-3.7\tau}\ln\frac{10}{3\tau}\ ,$$

and plotting kT against β: we show our results in Fig. 3. From our 255 observations, we have to discard 64 observations, for which the numerical solution of the `compTT` is not valid, resulting with 191 observations to proceed.

If the comptonization is due to electrons and occurs in the non-saturated regime, then the Compton parameter, y, (Rybicki & Lightman 1979), is given by (Petrucci et al. 2001),

$$y = 4\left(\frac{kT}{m_e c^2}\right)\left[1 + \left(\frac{kT}{m_e c^2}\right)\right]\tau(1+\tau)\ , \qquad (2)$$

where m_e is the rest mass of the electron (511 keV/c^2, in appropriate units). The powerlaw index in the hard X-ray domain expected from a spectra produced, once again, by thermal comptonization in a non-saturated regime, is then given by (Rybicki & Lightman 1979),

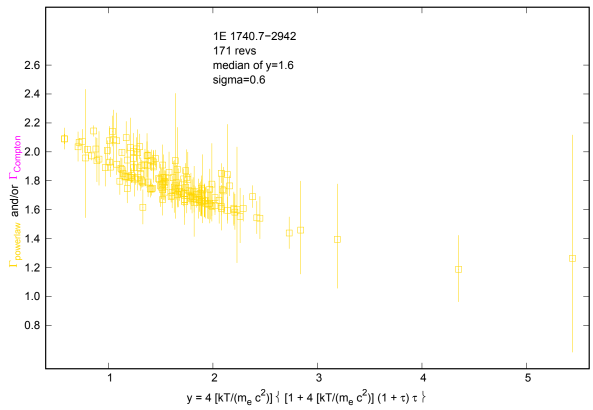

Figure 4. Plotted against the Compton parameter (y) are the two Γs: one obtained directly from the XSPEC's `powerlaw` (see Equation 1), and Γ_{comp} obtained using Equations (2) and (3). The inset shows the linear relationship between those two Γs. The median of y, as shown in the plot, is 1.6: we remind the reader that, for $y \sim 1$, the final spectrum produced by inverse Compton scattering is a powerlaw: for black hole in X-ray binaries, this powerlaw is observed in X-rays, and it is best sampled (i.e., where a better determination of Γ_{pl} is possible) in hard X-rays.

$$\Gamma_{\rm comp} = -\frac{1}{2} + \sqrt{\frac{9}{4} + \frac{4}{y}}\ . \qquad (3)$$

We then can follow to the characterization of the corona of 1E 1740.7−2942. When we refer to *characterization* it means that we're about to provide the temperature of the corona (kT) and its optical depth (τ). From 191 observations, we select those where Γ_{pl} and Γ_{comp} are in agreement to each other (within 10%: that is our adopt criterion). Fig.4 shows both Γs as a function of the Compton parameter, y. With this step, we're then left with 171 observations in which, as we mentioned earlier, soft X-ray photons up to, say, ∼1 keV, provided by an accretion disk, are comptonized to hard X-rays ($E > 20$ keV), in a thermal and non-saturated regime taking place at the source's corona. From those 171 observations, then, we can retrieve kT and τ. In Fig. 5 we show how the histograms of both Γs are similar for the 171 observations. The corona in 1E 1740.7−2942 has a temperature of 44±18 keV (data dispersion) and an optical depth τ of 1.5±0.6 (data dispersion).

Recent measurements of the distance, 8±1 kpc, to 1E 1740.7−2942 (Tetarenko et al. 2020) as well as a tentative mass (M = 5 $M_\odot$) for the source (Stecchini et al. 2020) combined with the flux measurements in the 20–200 keV range, have allowed us to produce one of the longest lightcurves of the source, as well as, for the first time in the literature, display it in Eddington units. This result is presented in Fig.6, finishing this section.

3. Discussions and Conclusions

The large database of ISGRI/INTEGRAL and a systematic approach in data reduction/analysis have allowed us to consistently study the corona in a black hole X-ray binary. We have thus characterized the corona at the black hole candidate 1E 1740.7−2942

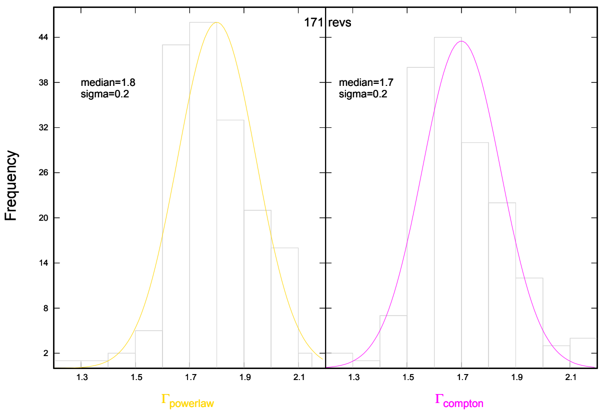

FIGURE 5. The histograms for both Γ: Γ_{comp} and Γ_{pl}. As shown in the Figure, they share, within statistics, the same (median) values, and are also quite similar, showing, in our opinion, solid evidence for the application of Equations (2) and (3), from which we can, thus, conclude the thermal and non-saturated nature of the 1E 1740.7−2942's corona. We can characterize it then further: $kT = 44{\pm}18$ keV and $\tau = 1.5 \pm 0.6$. The hard X-ray spectra in 1E 1740.7−2942 is the result of inverse Compton scattering of soft X-rays photons in its corona.

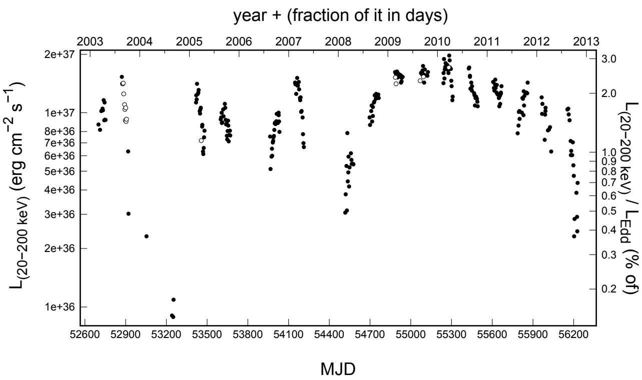

FIGURE 6. A lightcurve of 1E 1740.7−2942. In the Figure, 255 observations (filled circles) are the subject of this study. Sixteen points (open circles) are observations where we can fit neither a `powerlaw` nor a `compTT` model to the data obtaining an acceptable fit: in those situations, we used the `cutoffpl` model to obtain the flux. We were also able, for the first time, to show the luminosity of the source in Eddington units, due to a recent mass measurement and distance to the source (see text for details).

in the sense of providing its physical parameters: its optical depth and temperature. Given the temperature that we found ($kT = 44{\pm}18$ keV) it is immediately obvious to see that a big chunk of emission by black hole in X-ray binaries is in hard X-rays ($E > 20$ keV): emission in soft X-rays ($E < 20$ keV) is also dominated by this component, with the accretion disk being dominant, with its thermal emission, at $E \sim 1 - -4$ keV. It is the relative contribution of this two components (the thermal and the comptonized one) that is accounted for the different spectral states observed in black hole X-ray binaries. We have further offered a hint that the corona in 1E 1740.7−2942 is thermal and that the inverse Compton scattering within it occurs in a non-saturated regime. The physical grounds for these conclusions are the applicability of Equations (2) and (3), as well as the result presented in Fig. 5, that shows the powerlaw index behavior of the hard x-ray spectra of 1E 1740.7−2942. We can, further, conclude that the variations in the Γ_{pl} index (see Equation 1) are driven by small variations in, both, kT and τ. Extrapolating on this idea, it is our opinion that the observed differences in the Γ_{pl} in black hole X-ray binaries are driven by the corona. We've been able to explore this supposition, here, consistently, for the first time in the literature. We have not discussed how these variations affect the lightcurve presented in Fig. 6 in which, also the first time for 1E 1740.7−2942, could be displayed in L_{Edd} units. The sombrero model, as presented earlier, can explain the results obtained here from our observations/data analysis. In this model, the soft X-ray photons can be originated in the accretion disk, which will dominate the spectrum up to ∼ 4 keV, and then the corona will comptonize these photons, giving birth to the remaining (from, say, 5–200 keV, and beyond) spectrum. In the context of the Sombrero model, different spectral states arise due to the disk truncation. In literature, however, different explanations for the emergence are discussed (Kara et al. 2019). In this scenario, the different spectral states are the results of a *changing* corona, i.e., a corona that is not stable, geometrically. We cannot draw *any* conclusion on a geometrical stable corona in 1E 1740.7−2942 with the data shown here.

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