**XMM-Newton observations of the symbiotic recurrent nova T CrB: evolution of X-ray emission during the active phase**

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**ABSTRACT**

We present an analysis of the XMM-Newton observations of the symbiotic recurrent nova T CrB, obtained during its active phase which started in 2014 - 2015. The XMM-Newton spectra of T CrB have two prominent components: a soft one (0.2 - 0.6 keV), well represented by black-body emission, and a heavily absorbed hard component (2 - 10 keV), well matched by optically-thin plasma emission with high temperature \(kT \approx 8\) keV. The XMM-Newton observations reveal evolution of the X-ray emission from T CrB in its active phase. Namely, the soft component in its spectrum is decreasing with time while the opposite is true for the hard component. Comparison with data obtained in the quiescent phase shows that the soft component is typical only for the active phase, while the hard component is present in both phases but it is considerably stronger in the quiescent phase. Presence of stochastic variability (flickering) on time-scales of minutes and hours is confirmed both in X-rays and UV (UVM2 filter of the XMM-Newton optical monitor). On the other hand, periodic variability of \(6000-6500\) s is found for the first time in the soft X-ray emission (0.2 - 0.6 keV) from T CrB. We associate this periodic variability with the rotational period of the white dwarf in this symbiotic binary.

**Key words:** stars: individual: T CrB – stars: binaries: symbiotic – accretion, accretion disks –X-rays: stars.

1 INTRODUCTION

T CrB (HD 143454) is a symbiotic recurrent nova with two nova-like outbursts recorded by the modern astronomy in 1868 and 1946. It is a binary system with an orbital period of 227.57 days (Fekel et al. 2000) at a Gaia distance of \(806^{+33}_{-31}\) pc (Bailer-Jones et al. 2018). The cool star in this binary system is a red giant of a M4III spectral type (Müros & Schmid 1999) that fills its Roche lobe which facilitates accretion onto the more massive hot component, a white dwarf (Belczynski & Mikolajewska 1998; Stanishev et al. 2004).

The first X-ray detection of T CrB was with the Einstein observatory (Cordova et al. 1981), followed by studies with various X-ray observatories in the last two decades. The X-ray emission of T CrB is hard and highly absorbed (Luna et al. 2008; Kennea et al. 2009; Luna et al. 2018), so, it is a typical member of the class \(\delta\) of the X-ray sources among symbiotic stars: the X-rays from these objects likely originate from the boundary layer between an accretion disk and the white dwarf (Luna et al. 2013). Its X-ray emission shows strong stochastic variability both in the soft (< 10 keV) and hard (> 20 keV) energy bands (e.g., Luna et al. 2008; Ilkiewicz et al. 2016) that resembles the characteristics of the flicker noise (flickering), typical for accretion processes in astrophysical objects.

Recently, Munari et al. (2016) reported that in 2015 T CrB has entered a phase of unprecedented activity (but the optical brightening started yet in 2014), a super-active phase as named by these authors, that is similar to its state a few years before its nova-like eruption in 1946. However, Ilkiewicz et al. (2016) provided arguments that in the past T CrB has experienced numerous active phases and this in 2015 is just one such an active phase\(^1\). So, 2014-2015 marked the start of new activities in T CrB that manifest in optical, UV and X-rays and will provide valuable pieces of information about the physics of this symbiotic recurrent nova.

In this paper, we report results from the XMM-Newton observations of the symbiotic recurrent nova T CrB, obtained during its active phase which started in 2014 - 2015.
Newton observations of T CrB, carried out during its current active phase. In Section 2, we review the observational data. In Section 3, we present results from analysis of the X-ray emission of T CrB. In Section 4, we discuss our results and Section 5 presents our conclusions.

2 OBSERVATIONS AND DATA REDUCTION

T CrB was observed with XMM-Newton on 2018 January 30 (Observation ID 0800420201; PI: S. Zhekov) with a nominal exposure of ~ 28.0 ks. The source was clearly detected in X-rays (see Fig. 1) and good quality data were acquired with the European Photon Imaging Camera (EPIC) having one pn and two MOS detectors. The XMM-Newton Optical Monitor (OM)\(^2\) telescope allows for obtaining optical/UV data on a given target simultaneously with its X-ray data. Thus, six UV exposures in UVM2 filter were obtained that provided good quality UV light curves (LC) of T CrB.

X-rays. For the data reduction, we made use of the XMM-Newton SAS\(^3\) 16.1.0 data analysis software. The SAS pipeline processing scripts emproc and epproc were executed to incorporate the most recent calibration files (as of 2017 December 20). The data were then filtered for high X-ray background following the instructions in the SAS documentation. The corresponding SAS procedures were adopted to generate the response matrix files and ancillary response files for each spectrum. The MOS spectrum in our analysis is the sum of the spectra from the two MOS detectors.

\(^2\) for EPIC and OM see § 3.3 and 3.5 in the XMM-Newton Users Handbook, https://xmm-tools.cosmos.esa.int/external/xmm_user_support/documentation/uhb/

\(^3\) Science Analysis Software, https://xmm-tools.cosmos.esa.int/external/xmm_user_support/documentation/sas_usg/USG/

The extracted EPIC spectra (0.2 - 10 keV) of T CrB had ~ 2848 source counts in the 20.1-ks pn effective exposure and ~ 1538 source counts in the 26.3-ks MOS effective exposure. Also, we constructed the pn and MOS1,2 background-subtracted light curves of T CrB.

UV. We used the pipeline background-subtracted light curves of T CrB in the UVM2 filter (effective wavelength and width of 2310 Å and 480 Å, respectively) in units of counts s\(^{-1}\) which can be presented also in magnitudes using the zeropoint for the UVM2 filter.

Similarly, the data reduction (in X-rays) was done for the archive observation of T CrB carried out on 2017 February 23 (Observation ID 0793183601; Target of Opportunity) that provided EPIC spectra (0.2 - 10 keV) of T CrB with ~ 9230 source counts in the 37.5-ks pn effective exposure and ~ 3634 source counts in the 59.3-ks MOS effective exposure. We note that these data were already discussed in Luna et al. (2018).

For the spectral analysis, we used version 12.9.1 of XSPEC (Arnaud 1996).

3 RESULTS

3.1 An overview of the X-ray emission

The XMM-Newton observations of T CrB during its current active phase provide data of good quality that reveal some interesting global features of the X-ray emission from this symbiotic system.

In their analysis of the 2017 XMM-Newton observation, Luna et al. (2018) pointed out that there were two strong components in the (0.2 - 10 keV) X-ray spectrum of T CrB. Namely, a soft one that dominates the spectrum in the 0.2 - 0.6 keV energy range (well matched by blackbody emission), and a highly absorbed hard component at energies above 1.5 - 2 keV. It is interesting to note that the soft component is a new feature in the X-ray emission from T CrB that appeared only in the current active phase and was not present before that as illustrated by the Suzaku spectra (Luna et al. 2008).

As seen from Fig. 2 (left panel), these two components still dominate in the 2018 spectrum of T CrB with some noticeable changes: the soft component is becoming weaker with time (2018 vs 2017) while the opposite is valid for the hard component. Thanks to the higher hard X-ray flux, some spectral-line features are better seen in the 2018 spectrum of T CrB (Fig. 2; right panel), which is a basic illustration of the thermal origin of the hard component in its X-ray emission.

On the other hand, it is worth mentioning that there is a weak X-ray emission at ‘intermediate’ energies (0.6 - 2 keV; see Fig. 2, left panel), detected at a $> 5 \sigma$ level in all the EPIC spectra (pn and MOS). So, this emission is not a result from bad background subtraction and should be thus associated with T CrB. As seen from Fig. 2, the ‘intermediate’ component correlates with the hard component in the spectrum: its emission is stronger in 2018 than in 2017. We will return to this in Section 3.2.
3.2 Global Spectral Models

As discussed in Section 3.1, we need at least two components in the global spectral models to derive some physical properties of the X-ray emission from T CrB. However, if we adopt just two spectral components that are supposed to correspondingly match the strong soft emission (0.2 - 0.6 keV) and the highly absorbed hard emission (E > 2 keV), such a model cannot match the weak X-ray emission at 0.6 - 2 keV (see Fig. 2, left panel). The (0.6 - 2 keV) emission can be fitted successfully if we introduce an additional spectral component. Unfortunately, due to the limited photon statistics of this emission the model parameters of the third component cannot be constrained.

We recall that the X-ray emission in the (0.6 - 2 keV) range correlates with the highly absorbed emission at energies E > 2 keV (see above), and indeed our attempts to find a common spectral model for it and the strong soft emission (0.2 - 0.6 keV) ended with no success. So, one way of resolving this issue is to adopt the approach proposed by Luna et al. (2018), namely, to consider a partial-covering factor for the highly absorbed hard component.

First, we considered a spectral model with partial-covering absorption as in Luna et al. (2018) that consists of the following components: black body and cooling flow emission as basic ingredients, and a gaussian component, representing the Fe K-shell fluorescent line in the spectrum of T CrB. Second, we considered a similar model whose second spectral component is that of optically thin plasma emission. Such a choice is justified by the fact that the physical picture of cooling flow (typical for clusters of galaxies) is not adequate to that in an accreting binary system no matter whether such a model (with a cooling flow component) may provide acceptable fits to the observed spectra.

We fitted all the observed spectra (EPIC 2018 and 2017) simultaneously as the pn and MOS spectra of each individual data set shared identical model parameters. The chemical abundances were solar (Anders & Grevesse 1989) with no evolution between 2017 and 2018. To improve the quality

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4 We recall that cooling flows (CF) in clusters of galaxies are assumed to be spherically symmetric and such is the CF model in XSPEC. But, the gas flow in binary systems is not valid both for accretion from stellar wind and mass transfer due to Roche lobe overflow. This is also the case with the accretion disk boundary layer which is not a spherically-symmetric object, but its emission is supposed to be represented by the CF model (see Section 4).
Table 1. Global Spectral Model Results

| Parameter | BB + vmcf | BB + vapc |
|-----------|-----------|-----------|
|           | 2017      | 2018      | 2017      | 2018      | 2017      | 2018      |
| $\chi^2$/dof | 309/335 | 326/338 | 308/335 | 324/338 |
| N$_{H1}$ ($10^{20}$ cm$^{-2}$) | 5.19$^{+0.09}_{-0.05}$ | 5.24$^{+0.46}_{-0.32}$ | 5.17$^{+0.34}_{-0.26}$ | 5.18$^{+0.40}_{-0.33}$ |
| CF | 0.999$^{+0.001}_{-0.001}$ | 0.995$^{+0.001}_{-0.001}$ | 0.996$^{+0.001}_{-0.001}$ | 0.995$^{+0.001}_{-0.001}$ |
| N$_{H2}$ ($10^{22}$ cm$^{-2}$) | 43.3$^{+2.8}_{-1.9}$ | 33.1$^{+2.13}_{-1.22}$ | 38.2$^{+2.14}_{-1.9}$ | 42.8$^{+2.44}_{-1.9}$ |
| $kT_{BB}$ (keV) | 0.035$^{+0.001}_{-0.001}$ | 0.045$^{+0.002}_{-0.002}$ | 0.035$^{+0.001}_{-0.001}$ | 0.045$^{+0.002}_{-0.002}$ |
| $R_{BB}$ (km) | 2285$^{+464}_{-36}$ | 281$^{+65}_{-56}$ | 2063$^{+268}_{-23}$ | 232$^{+68}_{-23}$ |
| Fe | 0.96$^{+0.09}_{-0.07}$ | 4.50$^{+1.0}_{-0.8}$ | 3.58$^{+1.4}_{-1.2}$ | 3.84$^{+1.4}_{-1.7}$ |
| Ni | 4.62$^{+1.61}_{-1.61}$ | 4.62$^{+1.61}_{-1.61}$ | 3.85$^{+1.4}_{-1.4}$ | 3.82$^{+1.4}_{-1.4}$ |
| $kT_{max}$ (keV) | 11.28$^{+1.56}_{-0.58}$ | 18.52$^{+3.53}_{-3.53}$ | 14.67$^{+2.24}_{-2.24}$ | 14.67$^{+2.24}_{-2.24}$ |
| $M$ ($10^{-5}$ M$_\odot$ yr$^{-1}$) | 1.71$^{+0.22}_{-0.25}$ | 1.46$^{+0.37}_{-0.37}$ | 1.09$^{+0.21}_{-0.20}$ | 2.15$^{+0.45}_{-0.38}$ |
| $kT$ (keV) | 6.39$^{+0.39}_{-0.39}$ | 8.26$^{+0.44}_{-0.44}$ | 7.53$^{+0.48}_{-0.48}$ | 7.53$^{+0.48}_{-0.48}$ |
| EM ($10^{55}$ cm$^{-3}$) | 1.41$^{+1.08}_{-1.08}$ | 1.98$^{+0.94}_{-0.94}$ | 1.18$^{+0.94}_{-0.94}$ | 2.35$^{+0.94}_{-0.94}$ |
| $E_{0}$ (keV) | 6.45$^{+0.02}_{-0.02}$ | 6.38$^{+0.03}_{-0.03}$ | 6.48$^{+0.01}_{-0.01}$ | 6.45$^{+0.01}_{-0.01}$ |
| $F_{0}$ ($10^{-6}$ cts cm$^{-2}$ s$^{-1}$) | 3.50$^{+0.03}_{-0.03}$ | 6.64$^{+0.97}_{-0.97}$ | 4.00$^{+0.51}_{-0.51}$ | 6.29$^{+1.38}_{-1.38}$ |
| $F_{X}$ (0.2 - 10 keV) | (2067) | (187) | (1641) | (238) |
| $F_{X}$ (0.2 - 0.6 keV) | 0.14 | 0.14 | 0.14 | 0.14 |
| $log L_{BB}$ (erg s$^{-1}$) | 39.95 | 34.63 | 35.92 | 34.63 |
| $log L_{CC}$ (erg s$^{-1}$) | 33.45 | 32.29 | 33.46 | 32.29 |
| $log L_{H}$ (erg s$^{-1}$) | 32.64 | 32.81 | 32.57 | 32.54 |

Note. Results from fits to the EPIC spectra of T CrB obtained in 2017 February and 2018 January. The xspec models are: wabs(partcov + wabs(bbody + vmcf + vapc + gaussian) (Model A); the same as Model A but the parameters CF, N$_{H2}$ and $kT_{max}$ have the same values for the 2017 and 2018 spectra (Model B); wabs(partcov + wabs(bbody + vapc + gaussian) (Model C); the same as Model C but the parameters CF, N$_{H2}$ and $kT_{max}$ have the same values for the 2017 and 2018 spectra (Model D). Table 1 lists the parameters that are best fit by each model. The quality of these fits (see Model D) is very good and justifies such an assumption. On the other hand, our attempts to fit acceptable models with the solar density for the 2017 and 2018 spectra were not successful.

The x-ray luminosity and the x-ray luminosity are for a reference distance of d = 806 pc. Errors are the 1$\sigma$ errors from the fits.
3.3 Variability

Previous studies of T CrB showed that it possess strong stochastic variability in the X-ray and UV domains (e.g., Luna et al. 2008; Ilkiewicz et al. 2016; Luna et al. 2018). The XMM-Newton observations of T CrB allow to check whether such a variability is present during the current active phase. To do so, we fitted each LC with a constant, adopting \( \chi^2 \) fitting.

Figure 4 shows the total UV light curve for the 2018 data set in the UVM2 filter of the XMM-Newton OM (optical monitor). We note that the 2018 observation had six individual exposures (of ~ 3000 s each). We explored different binning of the LCs but no matter the time-bin size, stochastic variability (flickering) was always present. This result does not depend on the format of the light curve: it is valid for the LCs in flux units (counts \( s^{-1} \)) and in magnitudes.

In X-rays, we made use of the background-subtracted light curves from all the EPIC (pn, MOS1 and MOS2) detectors in the soft (0.2 - 0.6 keV), hard (2 - 10 keV) and total (0.2 - 10 keV) energy bands, adopting various binning with time bins between 100 and 1000 s. In all the cases under consideration, flickering was present both in the 2018 and 2017 data sets. The higher sensitivity of the pn detector results in LCs with much better quality compared to those from the MOS detectors, even if the latter were combined (MOS1+MOS2). This allowed us to search for periodic signal in the X-ray light curves of T CrB.

For this purpose, we applied the Lomb-Scargle method (Lomb 1976; Scargle 1982; see § 13.8 in Press et al. 1992) to the pn LCs of T CrB, since the XMM-Newton LCs are typically unevenly sampled data due to time intervals with high X-ray background. We analysed the soft, hard and total X-ray LCs. The Lomb-Scargle power spectrum indicated that a periodic signal was present in the soft (0.2 - 0.6 keV) emission of T CrB as the false-alarm probability was very low (< \( 10^{-5} \)), that is, the signal is highly significant: the smaller the value the more significant the signal (see § 13.8 in Press et al. 1992).

To check this result, we constructed a phase-averaged light curve by folding the original LC with the found period as the count rate was averaged within the size of the phase bin to minimize the contribution from the flickering. Such phase-averaged LCs could be very well matched by a simple sinusoidal function.

As an additional check, we performed time-resolved spectroscopy of the X-ray emission from T CrB. Namely, we re-extracted the pn spectra for each phase bin by combining all the X-ray emission with exposure time that exactly corresponds to that particular phase bin. We note that thanks to the good photon statistics of the EPIC-pn data of T CrB the individual phase-bin spectra have enough source counts (\( \geq 270 \) for the 2018 and \( \geq 820 \) for the 2017 spectra, respectively) which allows for their analysis in some detail. So, we fitted the phase-bin spectra with the same global models as discussed in Section 3.2. In these fits, we varied only the normalization parameters of the spectral components, while the other parameters were kept fixed to their values given in Table 1. We found that the flux variations of the soft X-ray emission from T CrB well correspond to the periodic signal detected by applying the Lomb-Scargle method to the X-ray LCs from the 2018 and 2017 XMM-Newton observations.

Some results from our analysis of the soft X-ray emission of T CrB aimed at searching for periodic signal are given in Fig. 5. We think it is conclusive that periodic signal (with a period of 6000 - 6500 s) was very likely present in the soft X-ray emission from the recurrent symbiotic nova T CrB in its active phase that started in 2014-2015.

We note that presence of flickering may result in suggesting some false signals from periodogram analysis. The result may depend on relative strength of the flicker noise and the real periodic signal. Some technical efforts might be needed to estimate the statistical significance of periodic signals, especially, those with short periods less than 1000 s or so (e.g., see Neustroev et al. 2005 and references therein).

However, we underline that our conclusion of the periodic (6000 - 6500 s) signal in the soft X-ray emission of T CrB is not just statistical and it is based on the accumulative evidence from the discussed above findings. Namely, (a) the Lomb-Sargle method indicates a periodic signal; (b) the light curves folded with the suggested period do confirm its presence; (c) the suggested period is also confirmed by time-resolved spectroscopy. However, the most important fact is the repeatability of the periodic signal: it is present in two different observational data sets, taken almost a year apart from one another, and the corresponding values of the period differ by less than 10%.

Finally, we also checked the correlation between the soft (0.2 - 0.6 keV) and hard (2 - 10 keV) emission in the 2018 and 2017 XMM-Newton LCs of T CrB. The value of the linear Pearson correlation coefficient between the soft and hard LCs is small both for the 2018 and 2017 observations (\( r \approx 0.07; -0.1 \)), thus, indicating very weak (or even no) correlation. Such a different behaviour of the X-ray LCs likely means that the soft and hard X-ray emissions originate from different regions in T CrB and might be subject to different formation mechanisms.

Figure 4. The UV light curves of T CrB from the XMM-Newton OM (optical monitor) observations in 2018 January. The LCs were binned at 60 s. The dashed line denotes the constant (mean) flux.
Figure 5. XMM-Newton light curves of T CrB. The LCs with a 100-s time bin are shown in the first row (slightly re-binned for presentation). The Lomb-Scargle power spectra are shown in the second row: the dashed line marks the false-alarm probability level of $10^{-5}$ (2018) and $10^{-8}$ (2017). The X-ray LCs folded with the derived period are given in the third row: each LC points presents the average count rate within a phase bin with a size of 0.125. The forth row presents the X-ray LCs in flux units (see text for details). The fit with a simple sinusoidal curve (with the noted period) is given by the dashed line.
4 DISCUSSION

The XMM-Newton observations of T CrB in 2018 January and 2017 February provided X-ray data with good quality. One of the most important results from our analysis of these data is the evolution of the X-ray emission from this symbiotic recurrent nova during its active phase.

We recall (see above) that the X-ray emission from T CrB has two basic (prominent) components that dominate its spectrum: a soft component (0.2 - 0.6 keV) and a hard component (2 - 10 keV). The hard component is heavily absorbed and we need to introduce a partial-covering absorption in order to match the weak X-ray emission at 0.6 - 2 keV (see Section 3.2). The results from our analysis (Table 1) show that the partial-covering factor could be assumed constant but changes of other parameters of the X-ray emission from T CrB are noticeable.

In general between 2017 February and 2018 January, the soft emission (0.2 - 0.6 keV) has decreased while the hard emission (2 - 10 keV) has increased and the flux of the Fe K fluorescent line has increased as well.

More specifically, the temperature of the black-body component, representative for the soft emission, has increased by ~28% while its luminosity has decreased by more than an order of magnitude. On the other hand, the flux of the hard component has increased by a factor of ~2 and there are indications that its temperature has increased as well, but, we recall that models with the same (equal) plasma temperatures of the hot component also provided very good fits to the observed spectra of XMM-Newton (see Table 1).

All these changes are an important characteristic of the X-ray emission from T CrB during its current active phase and thus provide valuable pieces of information about the origin of X-rays in this symbiotic binary. We recall that the boundary layer between the accretion disk and the white dwarf is the most likely place where the X-rays form in T CrB (Luna et al. 2013; Luna et al. 2018). To better understand the physics of this X-ray formation mechanism, it is important to see how the characteristics of the X-ray emission during the active phase compare with those in a non-active (quiescent) phase. For this purpose, the results from our analysis of the XMM-Newton observations in 2018 and 2017 should be ‘projected’ on those from X-ray observations taken before the current active phase started.

Our archival search showed that X-ray data suitable for such a comparative study, that is, providing spectra in the 0.2 - 10 keV energy range, have been obtained with Suzaku and Swift observatories. There is one Suzaku observation taken in 2006 September, that is, before the current active phase. On the other hand, there are numerous Swift observations carried out both in the quiescent phase (2005 June - 2015 September) as well as during the active phase (2017 January - 2018 December). To derive the global characteristics of the X-ray emission from T CrB, we considered the spectra from the Suzaku observation and two total Swift spectra, each of the latter representative correspondingly of the X-ray emission before and after the beginning of the active phase in 2014-2015. The data reduction and spectral analysis are given in Appendix A.

One very important global characteristic of the X-ray emission from T CrB is that while the heavily absorbed hard component (2 - 10 keV) is always present, the strong soft component (0.2 - 0.6 keV) is present only in the active phase.

The appearance of the strong soft component was first reported in the analysis of the XMM-Newton observation of 2017 February (Luna et al. 2018). In addition, we note that this component was not present in the Suzaku and Swift data, taken before the active phase, while signs of this component were found in all of the Swift observations during the active phase (see also Fig. A1). Unfortunately, there are no Swift observations (or of another X-ray observatory) in the period 2015 October - 2016 December, thus, the earliest time the soft component was detected is on 2017 January 18 (Swift ObsID 00045780903).

Interestingly, although the hard component is always seen in the X-ray spectrum of T CrB, its strength is quite different in the quiescent and active phases, namely, it is much weaker in the latter. This is well illustrated by the observed flux of T CrB in the (1.5 - 10 keV) energy band, for there is no contribution from the soft component at these energies. As seen from Fig. 6 (left panel), the hard-component flux in the quiescent phase is at least one order of magni-

Figure 6. The long-term light curve of T CrB from observations with some X-ray observatories. Left panel: the observed flux in the 1.5 - 10 keV energy range. The dotted lines mark the 1σ-confidence range on the Swift flux, while that for the Suzaku and XMM-Newton fluxes is within the size of the corresponding symbols denoting the flux values. Right panel: the intrinsic (unabsorbed) flux in the 0.2 - 80 keV energy range of the hard component in the X-ray spectrum (the corresponding accretion rate is shown on the right-hand side y-axis).
tude larger than it is in the active phase. This is also the case with the intrinsic flux of the hard component in a broad energy range, 0.2 - 80 keV, that is representative for the hard-component luminosity (Fig. 6, right panel). We note that the typical (average) temperature of the hard component in the quiescent phase is T = 16.23 keV (see Table A1), so, it is considerably higher (by a factor of ≈2) than it is in the active phase (see Models C and D in Table 1). So, there is a clear trend: the stronger the hard component, the hotter the plasma emitting the hard X-rays from T CrB.

In order to explain (at least qualitatively) all these global properties of the X-ray emission from T CrB in the quiescent as well as in the active phase, the following physical picture seems reasonable, we believe.

On a global scale, as discussed by Luna et al. (2018) the mechanism of activity in T CrB could be similar to that suggested for the recurrent nova RS Oph. Namely, the nova outburst is a result from thermonuclear burning on the surface of the white dwarf (WD). The necessary ‘fuel’ is deposited from the companion star through the accretion disk (AD) around the WD. Instabilities in the AD build up the necessary amount of gas through numerous phases of activity (Wynn 2008; Nelson et al. 2011; Bollimpalli et al. 2018). And, we witness an active phase in T CrB right now.

Since T CrB is a symbiotic star of the δ class sources of X-ray emission, it is suggested that its X-rays originate from the accretion disk boundary layer (ADBL) in this white dwarf + M-giant binary system (Luna et al. 2013; Luna et al. 2018).

We think it is reasonable to assume that the accretion disk is in steady-state conditions, when T CrB is in quiescent phase, so, the ADBL produces hard and strong X-ray emission. We note that the gas velocity in a Keplerian orbit close to the white dwarf in T CrB is ≥ 5000 km s\(^{-1}\) (\(M_{WD} = 1.2 M_{\odot}\), Belczynski & Mikolajewska 1998; \(R_{WD} = 5000\) km as assumed in Luna et al. 2018), so, high temperatures of > 10 keV are potentially possible (e.g., via shocks or viscous heating).

When instabilities develop, the ADBL transforms and some considerable amount of AD material is being delivered onto the WD surface, thus, the active phase is switched on. However, it may take some time all the observational features of an active phase to develop: e.g., the optical brightening started yet in 2014 (Manari et al. 2016), the hard X-ray component was still strong in 2015 September but at the same time the soft component was not present (evident from the Swift observations, this study; and from the NuSTAR observation, Luna et al. 2019).

The supplied material is located near the AD equator and may be gradually diffuses to the WD equator if the WD is inclined with respect to the plane of the binary orbit. This on-the-surface material is dense and its emission resembles that of a black body. Thus, the soft component appears in the X-ray spectrum of T CrB. In such a case, the 6000-6500-s periodic variability of the soft component emission (see Section 3.3 and Fig. 5) should correspond to the WD rotational period. So, the rotational velocity at the equator of the WD in T CrB should be \(\approx 5\) km s\(^{-1}\) for the adopted WD radius (see above) - a value that is not atypical for single WDs (e.g., Karl et al. 2005; Berger et al. 2005).

Since instabilities have delivered quite a bit of material onto the WD surface, some of the ADBL material should have been thus ‘evacuated’ and as a result the hard component in the X-ray spectrum of T CrB becomes weaker in the active phase. This may explain the almost one-order of magnitude difference in the effective accretion rate between the quiescent and active phases (see Fig 6, right panel). We note that the effective accretion rate was estimated in the standard steady-state AD picture, namely, assuming that one half of the total accretion energy is released by the AD itself and one half of it is released in the ADBL (\(\dot{L}_{\text{acc}} = G M \dot{M} \text{WD} / R \text{WD}\), where \(\dot{L}_{\text{acc}}\) is the total accretion luminosity, \(\dot{M}\) is the accretion rate and \(G\) is the gravitational constant). We have to keep in mind that changes in the effective accretion rate onto the WD surface do not imply changes of the global accretion rate from the donor M-giant star. The former indicate the conditions only in the inner part of an AD, that is, of its boundary layer, which could have been affected by development of instabilities.

During the AD evolution back to its steady-state conditions, the ADBL is gradually building up, thus, its emission (the hard component) is becoming stronger and it will eventually reach its flux level typical for the quiescent phase.

Interestingly, the ADBL plasma has higher temperature in the quiescent phase in comparison with the active phase. The reason could be that when instabilities deliver the AD gas onto the WD surface they clear off the innermost and hottest part of the ADBL material. As a result, the plasma temperature of the hard component lowers in the active phase. We note that this is just a qualitative explanation of this temperature difference, so, future observations and numerical AD models would be very helpful to get further insights of the physical processes responsible for it.

On the other hand, no matter whether T CrB is in quiescent or active phase the hard component in its spectrum is always highly absorbed. This X-ray absorption should be of local origin for its value is more than two orders of magnitude above that of the interstellar absorption towards T CrB. Also, analysis of the X-ray emission from T CrB has lead to suggestion of the partial-covering high X-ray absorption (e.g., Luna et al. 2018). However, the value of partial-covering factor is very close to unity (see also Table 1) since a very small amount of X-ray emission is required to ‘leak’ out in order to explain the weak emission detected in the 0.6 - 2 keV energy range. Such a result could be suggestive of some quite special geometry effects.

We underline that the high X-ray absorption in T CrB with a partial-covering factor being extremely close to unity is difficult to comprehend. Luna et al. (2018) discussed this issue in some detail and suggested that its resolution could be the presence of a clumpy wind from the accretions disk or the physical picture could be similar to that of the scattering model for the symbiotic binary CH Cyg (Wheatley & Kallman 2006): the latter requires highly ionized polar cavity in the AD wind.

On the other hand, if no AD wind is present in T CrB, could an alternative, although speculative, explanation be the following? Since the hard component is associated with the ADBL around the white dwarf in this symbiotic binary and this boundary layer likely has small radial extension, the high X-ray absorption might be due to the accretion disk itself. Also, X-rays from the top surface of the ADBL will not be absorbed, thus, providing the small ‘leak-out’ emission in the 0.6 - 2 keV energy range. In the no-wind case, the
soft component (black-body emission forming on the WD surface) will not be subject to high X-ray absorption, if the AD/orbital inclination is not too close to 90 degrees and the AD is indeed geometrically thin; an observer would see the soft component directly and only the ISM absorption will matter, provided the M-giant wind is not too massive.

For spherically-symmetric stellar wind with constant velocity and solar abundances, the hydrogen column density of the M-giant wind along the line of sight between the white dwarf in T CrB and an observer is:

$$N_{H,\text{wind}} = 1.4 \times 10^{20} \frac{M_\odot}{v_{10} \sin i} \frac{5 - \alpha}{\cos \alpha} \text{ cm}^{-2}$$

where $M_\odot$ is the mass-loss rate in units of $10^{-9}$ M$_\odot$ yr$^{-1}$, $v_{10}$ is the wind velocity in units of 10 km s$^{-1}$, $a_{\text{wind}}$ is the binary separation in astronomical units, $\alpha$ is defined by $\cos \alpha = V \cos^2 \iota \sin^2 \omega + \cos \omega$, $\omega = 2\pi \phi$, $0 \leq \phi \leq 1$ is the orbital phase ($\phi = 0$ is the time of maximum radial velocity as in Fekel et al. 2000), $a < 0$ for $\phi > 0.5$, $i$ is the inclination angle of the binary orbit.

Using the ephemeris from Fekel et al. (2000), we derive that the XMM-Newton observations of T CrB were carried out at orbital phases of 0.954 (2018 January) and 0.455 (2017 February), that is very close to binary quadratures. Given the binary parameters of T CrB ($a = 0.9$ au, $i = 60^\circ$; see table 2 of Belczynski & Mikolajewska 1998), wind velocity of 10-30 km s$^{-1}$ and requiring that the M-giant wind contributes no more than 10% of the ISM column density derived from analysis of the X-ray spectra of T CrB (see parameter $N_{\text{H,I}}$ in Table 1), we estimate that the mass-loss rate of the M-giant stellar wind should not be considerably larger than $5 \times 10^{-10}$ M$_\odot$ yr$^{-1}$.

We note that the M-giant wind is an X-ray absorber detached from the X-ray formation region (i.e., the ADBL, and WD surface) in T CrB. So, this estimate is valid no matter if both, soft and hard, spectral components are subject to the partial-covering high absorption or only the hard component is. The XMM-Newton observations thus provide more stringent constraints on the mass-loss rate of the M giant in T CrB in comparison with the radio data that have put an upper limit of $8.7 \times 10^{-9}$ M$_\odot$ yr$^{-1}$ (the upper limit from table 2 in Seaquist et al. 1993 was scaled to the Gaia distance of 806 pc to T CrB).

Finally, it is generally accepted that the Roche lobe overflow of the M giant is the main source of accretion on the WD in the T CrB binary. So, the total accretion rate is not known in advance. If the M giant has a stellar wind, some part of it (no more than a half, based on the binary parameters) may add to the total accretion rate. The latter could in turn be estimated from the X-ray luminosity of the hard X-ray component which is associated with the ADBL.

As seen from Fig. 6 (right panel), the accretion rate in the quiescent state is not higher than $10^{-9}$ M$_\odot$ yr$^{-1}$ and that during the active phase is quite low ($< 10^{-10}$ M$_\odot$ yr$^{-1}$). So, it does not seem feasible that a considerable amount of accreted material will be accumulated on the surface of the WD that may lead to a nova outbursts with a recurrence period of 80 years (e.g., see tables 2 and 3 in Yaron et al. 2005). But, taking into account that the gravitational energy of the accreted material also powers the soft component, the situation may change. Namely, the accretion rate in active phase could be increased by a factor of a few or even boosted considerably ($\sim 10^{-7}$ M$_\odot$ yr$^{-1}$), depending on whether the soft component is subject only to the ISM absorption or is subject to the partial-covering absorption (see luminosity values log $L_{\text{BB}}$, log $L_{\text{MC}}$, log $L_{\text{H}}$ in Table 1). However, the global spectral fits do not give preferable fits for either of these cases: there are cases when the quality of fits is equal (see Section 3.2). So, future X-ray observations, both in the current active phase as well as in the next after it quiescent phase, will be very important to get further details on this important issue.

## 5 Conclusions

In this work, we presented the XMM-Newton data of T CrB, obtained during its active phase which started in 2014-2015, as well as some data taken with Suzaku and Swift in the quiescent phase of this symbiotic recurrent nova. The basic results and conclusions from our analysis of these data are as follows.

(i) The XMM-Newton spectra of T CrB have two prominent components: a soft one (0.2 - 0.6 keV), well represented by black-body emission, and a heavily absorbed hard component (2 - 10 keV), well matched by optically-thin plasma emission with high temperature ($kT \approx 8$ keV). The soft component was detected for the first time in the 2017-February observation (Luna et al. 2018) and it is present in the 2018-January observation as well. In addition, a weak but statistically significant (> 5σ level) emission is also present at energies 0.6 - 2 keV.

(ii) Relatively strong emission-line features are also seen (especially in the 2018 data) at high energies: the K-shell fluorescent Fe lines at ~ 6.4 keV (Fe K); the iron He-like triplet at ~ 6.7 keV (Fe XXV); the Fe XXVI L$_{\alpha}$ at ~ 6.97 keV (Fe XXVI) and the nickel He-like triplet at ~ 7.8 keV (Ni XXVII). Presence of such lines is a sold sign of the thermal origin of the X-rays from T CrB.

(iii) The XMM-Newton observations reveal evolution of the X-ray emission from T CrB in its active phase. Namely, the soft component in its spectrum is decreasing with time (2018 vs 2017) while the opposite is true for the hard component. Comparison with data obtained in the quiescent phase (earlier than 2016) shows that the soft component is typical only for the active phase, while the hard component is present in both phases but it is considerably stronger in the quiescent phase.

(iv) Presence of stochastic variability (flickering) on time-scales of minutes and hours is confirmed both in X-rays and UV (UVM2 filter of the XMM-Newton optical monitor). On the other hand, periodic variability of 6000-6500 s is found for the first time in the soft X-ray emission (0.2 - 0.6 keV) from T CrB.

(v) The basic characteristics of the X-ray emission from T CrB could be described in the framework of the following physical picture. Since T CrB is of the class δ of the X-ray sources among symbiotic stars, its heavily absorbed hard component should form in the boundary layer between the white dwarf and the accretion disk in this symbiotic binary (e.g., Luna et al. 2013; Luna et al. 2018). Development of instabilities results in delivering a considerable amount of the ADBL material onto the surface of the white dwarf in a relatively short period of time. This marks the beginning of an active phase. That material becomes optically thick and

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thus has black-body X-ray emission (the soft component in the X-ray spectrum). So, the 6000-6500-s periodicity of the soft component is related to the rotational period of the white dwarf. During the AD evolution back to its steady-state conditions, the ADBL is gradually building up, thus, the hard component in the T CrB spectrum will eventually return to its high level of the quiescent phase. Note that this picture is just an attempt to qualitatively explain the observational facts about the X-ray emission from T CrB. Future X-ray observations, both in the current active phase as well as in the next after it quiescent phase, will be very important to get further insights about the physics of this enigmatic symbiotic recurrent nova.

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APPENDIX A: X-RAY OBSERVATIONS OF T CrB WITH Suzaku AND Swift

Here, we briefly describe the data reduction and spectral modelling of the Suzaku and Swift data of T CrB. Suzaku. T CrB was observed by Suzaku on 2006 September 6 (ObsID 401043010) with a nominal exposure of 46.3 ks. The basic data for our analysis are from the X-ray Imaging Spectrometers (XIS) on-board Suzaku. We note that one of them (XIS1) is back-illuminated (BI) while the other three (XIS0, XIS2, XIS3) are front-illuminated (FI) CCDs which allows the extracted spectra from the latter be combined for further analysis. We extracted X-ray spectra of T CrB from the filtered and screened pipeline events files using the 3 × 3 observational mode which resulted in a 38.2 ks effective exposures providing 10847 and 39049 source counts in the (0.2 - 10 keV) energy range for the BI and total FI (XIS0+XIS2+XIS3) spectrum, respectively. We adopted the current calibration database for Suzaku, XIS (20181010) and X-Ray Telescope (XRT; 20110630), to generate the response matrix (RMFs) and ancillary files (ARFs). We note that the Suzaku telescopes have spatial resolution of ~2 arcmin (expressed as Half-Power Diameter) but there are no strong X-ray sources in vicinity of T CrB (Fig. 1), so, the Suzaku spectra should be safely associated with it.

Swift. T CrB was observed multiple times in 2005 June 17 - 2018 December 19 (ObsID from 00035171001 to 00035171006; 00081659001 and 00081659002; and from 00054776001 to 00054776039) with typical exposure time from less than 1 ks to 10 ks. Following the Swift XRT Data Reduction Guide6, we extracted the source and background

6 see The Suzaku Data Reduction Guide: http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/arc/

7 http://swift.gsfc.nasa.gov/analysis/xrt_swguide_v1.2.pdf

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spectra for each observation. Extraction regions had the same shape and size for each data set. For our analysis, we used the response matrix (xswp0to12src_20010101v014.rmf) provided by the Swift calibration files\footnote{http://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/swift/} as of 2019 January, and we also used the package xrtmkarf to construct the ancillary response file for each data set.

Since we are interested in the global characteristics of the X-ray emission from T CrB, we considered the spectra from the Suzaku observation and two total Swift spectra, each of the latter representative of the X-ray emission in the quiescent and active phase, respectively. In these total Swift spectra, only data sets with a minimum of 20 source counts were included, thus, the total number of source counts are 3340 (quiescent phase) and 884 (active phase). We note that the data of the Swift observations during the active phase (2017 January - 2018 December) do not have good photon statistics; only one individual spectrum has more than a hundred source counts. As a result, the mean Swift spectrum from observations during the active phase is quite noisy. For the spectral analysis, the Suzaku spectra were re-binned to have a minimum of 50 counts per bin, while the Swift spectra were re-binned with a minimum of 20 (quiescent phase) and 10 (active phase) counts per bin.

To facilitate the comparison with the results from the Swift spectra, we fitted simultaneously all three spectra (two from Suzaku and one from Swift) from the observations before the beginning of the active phase as they shared the same values of the model parameters that determine the spectral shape: the partial-covering absorption, the plasma temperature of the hard component. Due to the low quality of the mean Swift spectrum in the active phase (especially, at high energies), the model parameters for the hard component and the partial-covering absorption were kept fixed to their values derived from analysis of the XMM-Newton spectra (see Table A1). XIS (FI) denotes the total spectrum from the three front-illuminated detectors, while XIS (BI) denotes the spectrum from the back-illuminated detector on board Suzaku.

Table A1. Suzaku and Swift Spectral Fits

| Parameter | BB + vapec |
|-----------|------------|
|           | quiescent  | active    |
| $\chi^2$/dof | 1130/1162  | 60/71     |
| $N_{H,1}$ (10$^{20}$ cm$^{-2}$) | 5.18  | 5.18      |
| CF        | 0.9986$^{+0.0002}_{-0.0002}$ | 0.994     |
| $N_{H,2}$ (10$^{22}$ cm$^{-2}$) | 27.5$^{+0.30}_{-0.30}$ | 38.1      |
| $kT_{BB}$ (keV) | 16.23$^{+0.42}_{-0.44}$ | 7.53      |
| $R_{BB}$ (km) | 117$^{+71}_{-60}$ |            |
| $T_{P}$ (keV) | 4.2$^{+0.5}_{-0.4}$ | 7.53      |
| $E_{T}$ (keV) | 6.42$^{+0.80}_{-0.70}$ | 6.40      |
| $F_{T}$ (10$^{-6}$ cts cm$^{-2}$ s$^{-1}$) | 57.2$^{+0.2}_{-0.3}$ | unconstrained |
| $F_X$ (0.2 - 10 keV) | 15.8  | 1.07      |
| $F_X$ (0.2 - 6 keV) | 0.003 | 0.16      |
| $F_X$ (0.2 - 0.6 keV) | 0.003 | (127)     |
|           | (4.9)     |            |

Note. Results from fits to the Suzaku and Swift spectra of T CrB. The adopted XSPEC model is: wabs(partcov+wabs)(bbbody+vapec) + gaussian. The labels ‘quiescent’ and ‘active’ mark results for the spectra obtained before 2016 (Suzaku and Swift) and after 2016 (Swift), respectively. All abundances have the same values as in the fits to the XMM-Newton spectra. For description of tabulated quantities see Notes to Table 1. All fluxes are in units of 10$^{-12}$ erg cm$^{-2}$ s$^{-1}$. For the flux values in column ‘quiescent’, the first pair of rows gives the Suzaku results and the second pair of rows gives the Swift results. Errors are the 1σ values from the fits.

Table 1). Results from the global fits to the Suzaku and Swift spectra are given in Table A1 and Fig. A1.

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